

Large Opacity Variations in the $z \sim 5.5$
Lyman- α Forest:
Implications for Cosmic Reionization

Anson D'Aloisio
University of Washington

In collaboration with: Matt McQuinn (UW), Hy Trac (CMU),
and Phoebe Upton Sanderbeck (UW)

UC Berkeley Cosmology Seminar, 9/22/15

Outline

Problem: Larger-than-expected variations in Ly α opacity of IGM at $z > 5$. ([Becker et al. 2015: 1407.4850](#))

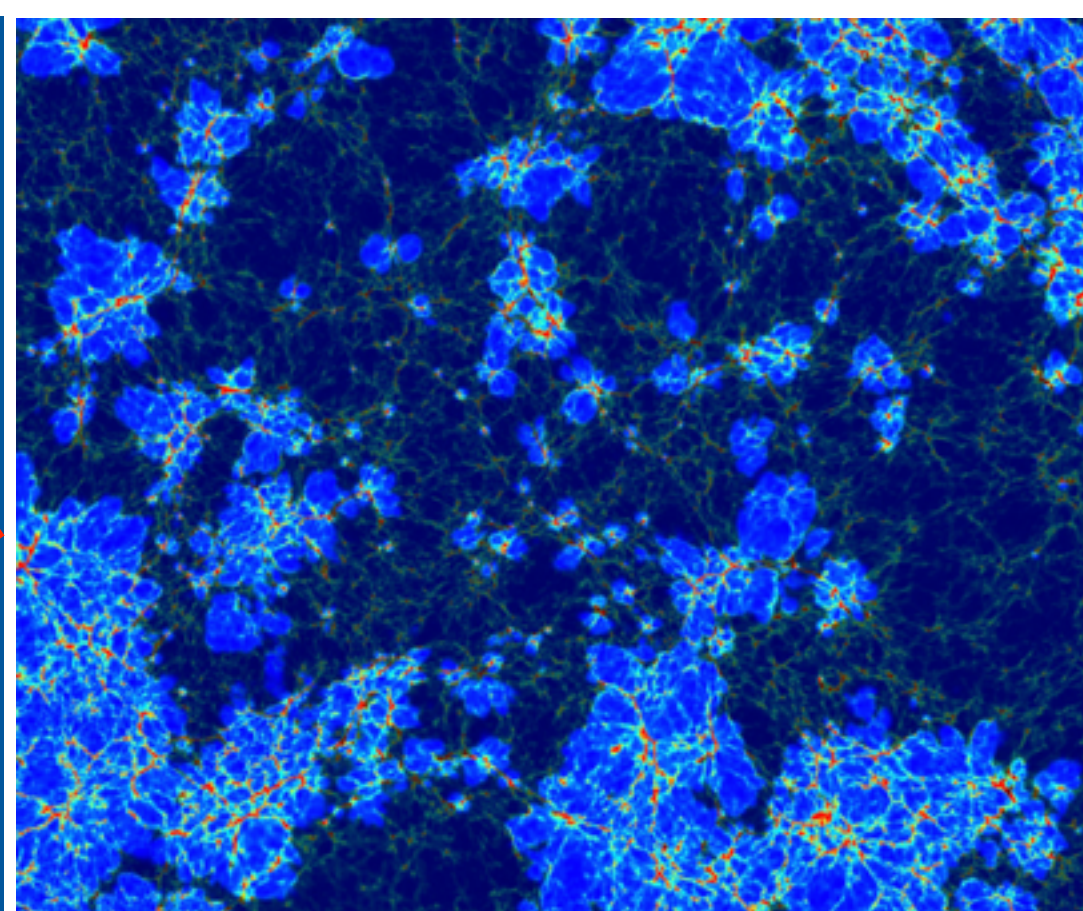
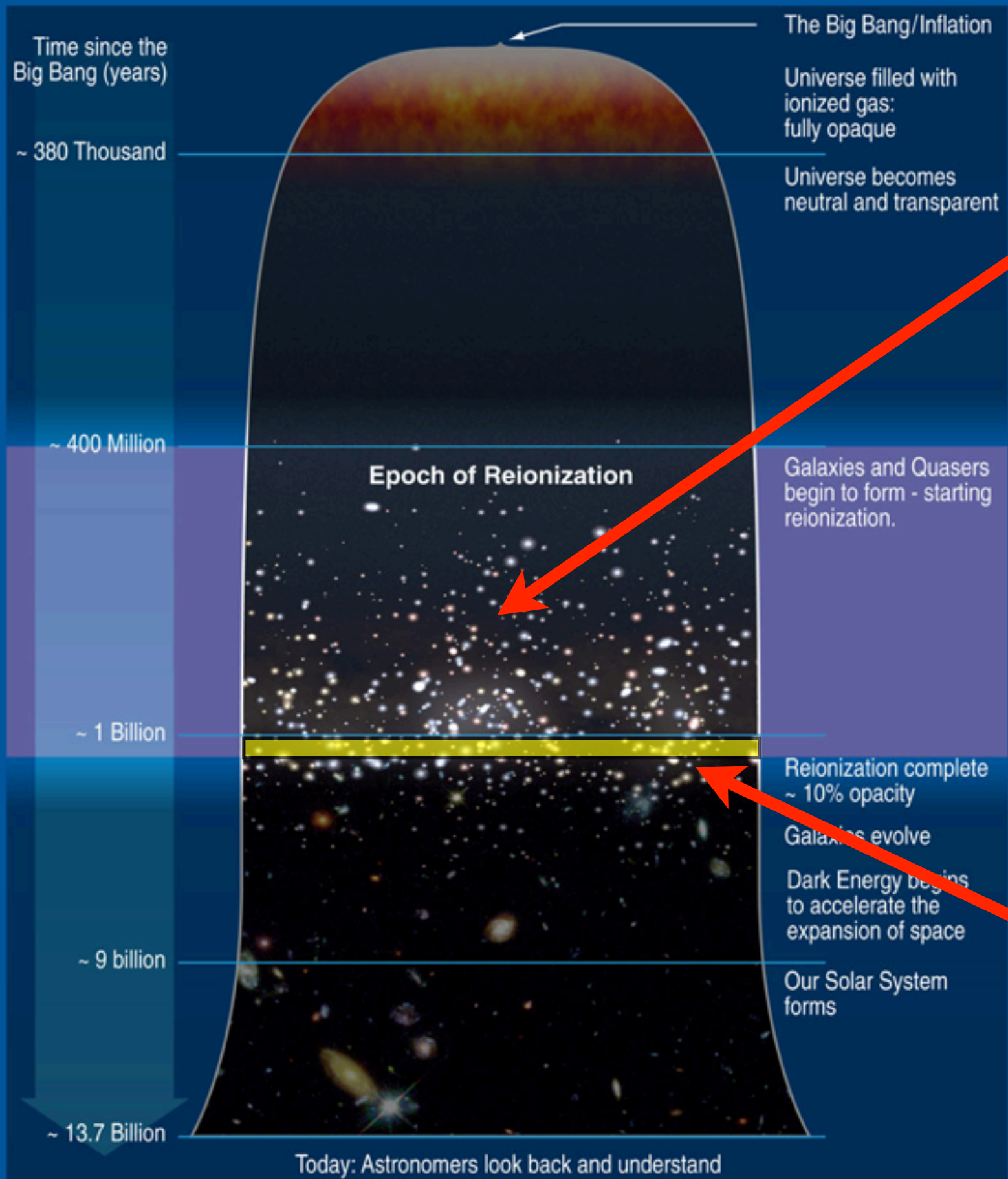
Possible Explanations:

(1) Inhomogeneous ionizing background from rare sources (e.g. quasars). ([Chardin et al. 2015: 1505.01853](#))

(2) Inhomogeneous ionizing background/mean free path. ([Davies and Furlanetto 2015: 1509.07131](#))

(3) Relic temperature fluctuations from patchy reionization. ([D'Aloisio, McQuinn & Trac 2015: 1509.02523](#))

First Stars and Reionization Era



*Image by Hyunbae Park, CoDa Simulation (PI: P.R. Shapiro)

- Timing, structure, and even sources of reionization unknown!

- Focus of this talk: the $5 < z < 6$ Ly α forest

Robust constraints on reionization:

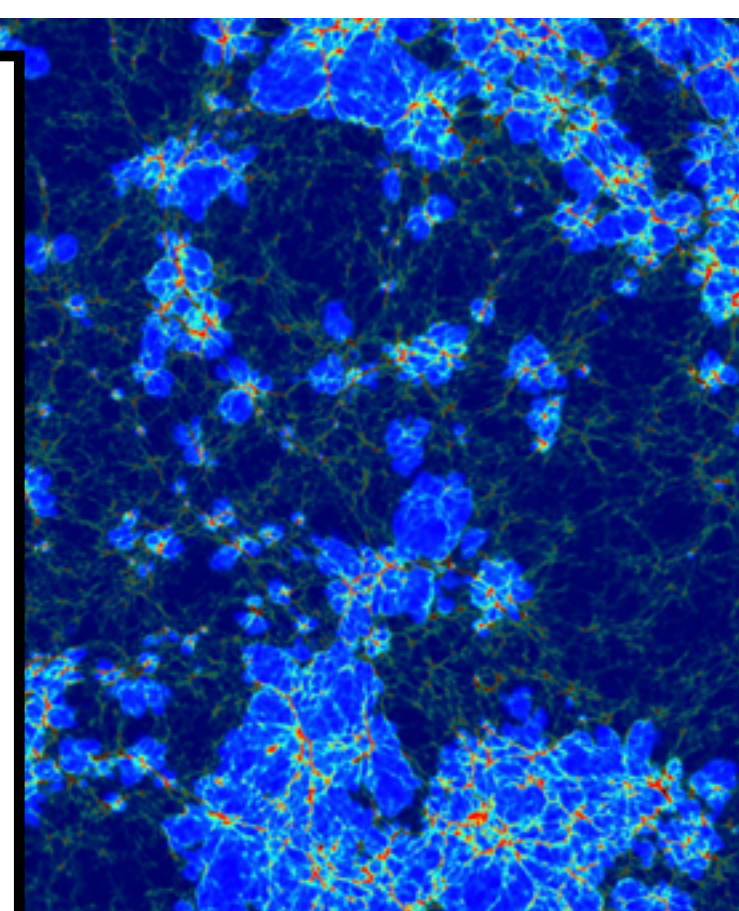
- (1) CMB -- Reionization roughly half-way complete at $z = 9$
- (2) Ly α forest -- Reionization largely complete by $z \sim 6$.
(but could have ended earlier)

Other observations:

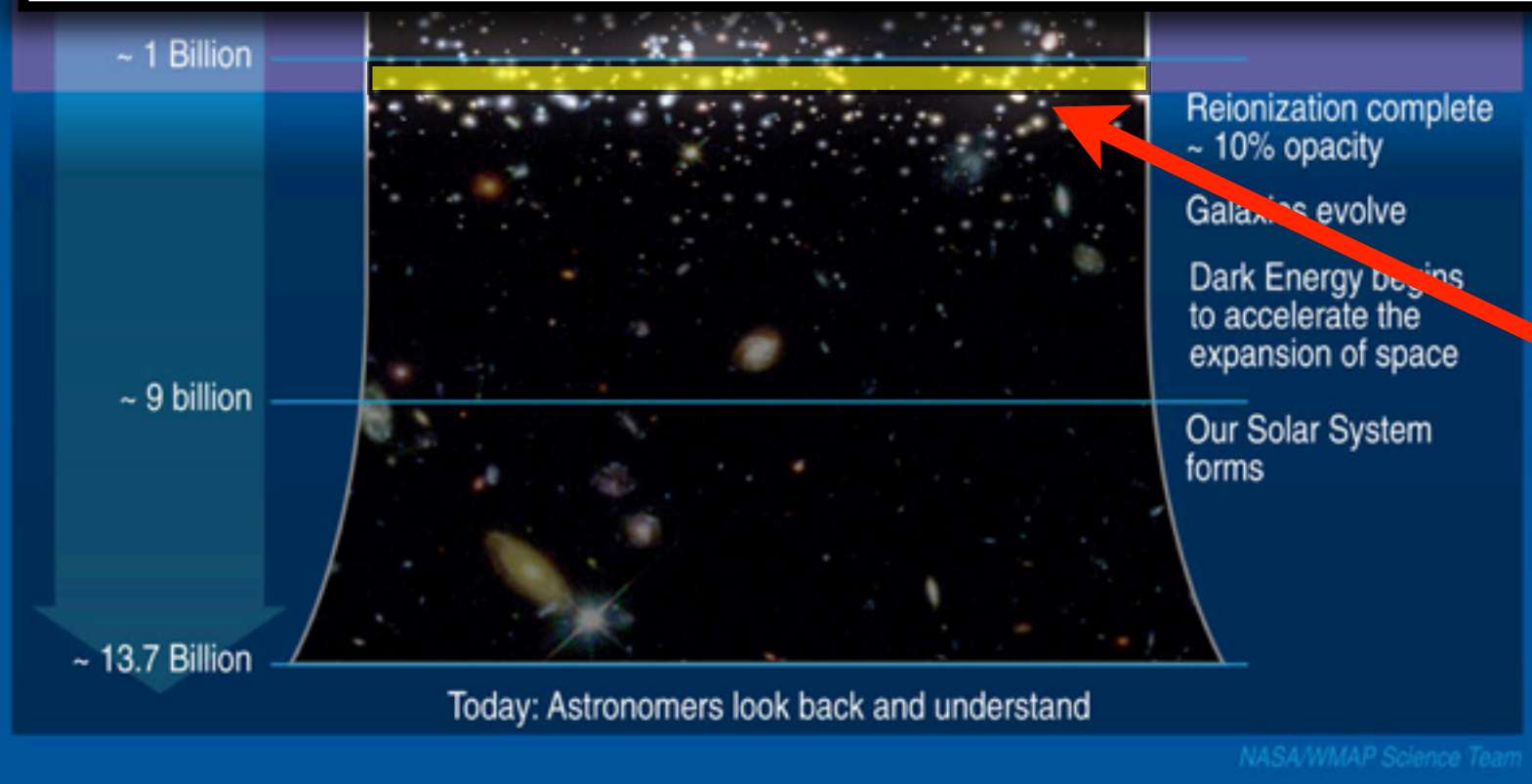
- (3) Kinetic Sunyaev-Zel'dovich Effect; (4) High- z Ly α emitters;
- (5) High- z gamma ray bursts; (6) 21cm

The future!

21cm



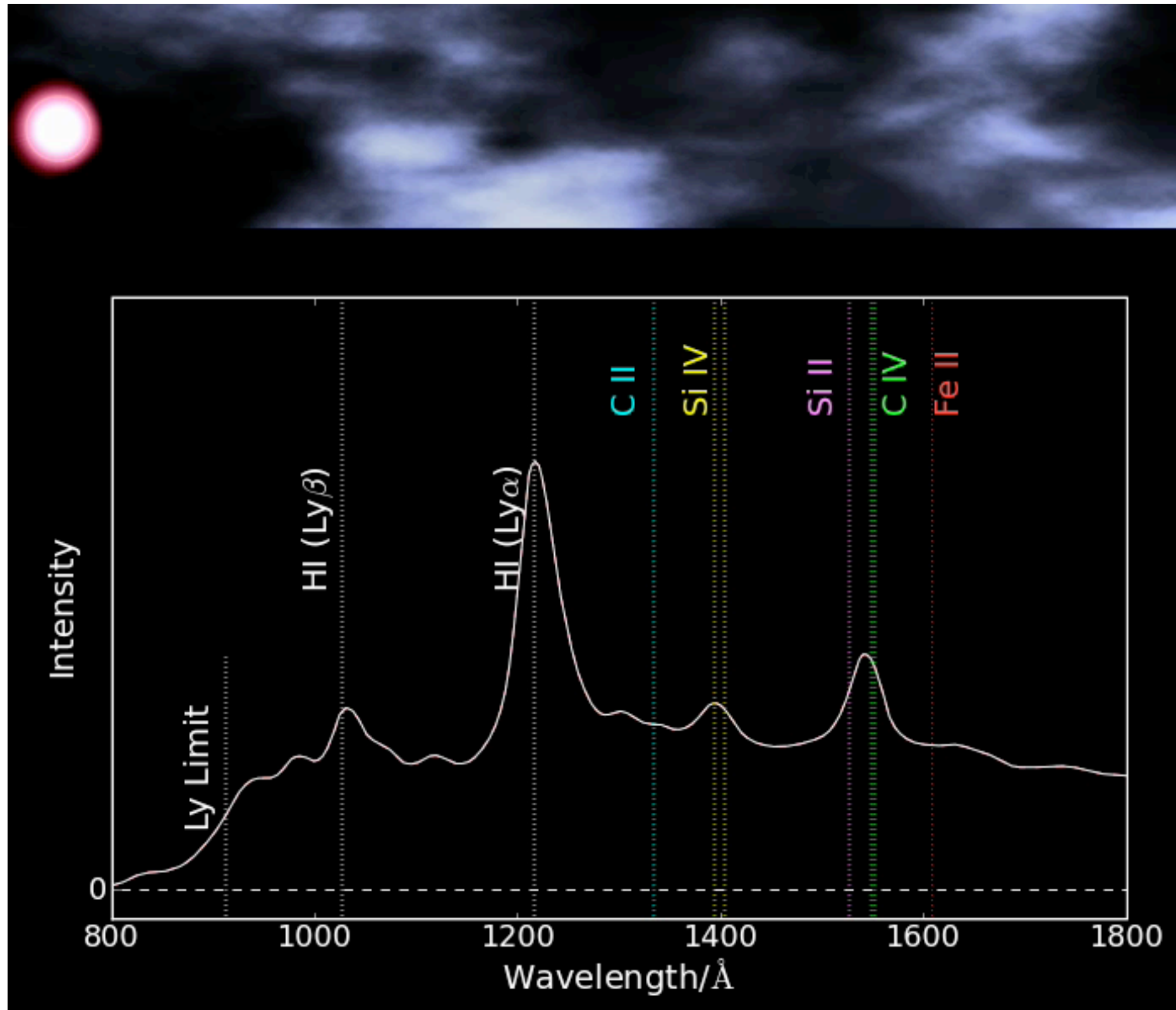
Park, CoDa Simulation (PI: P.R. Shapiro)



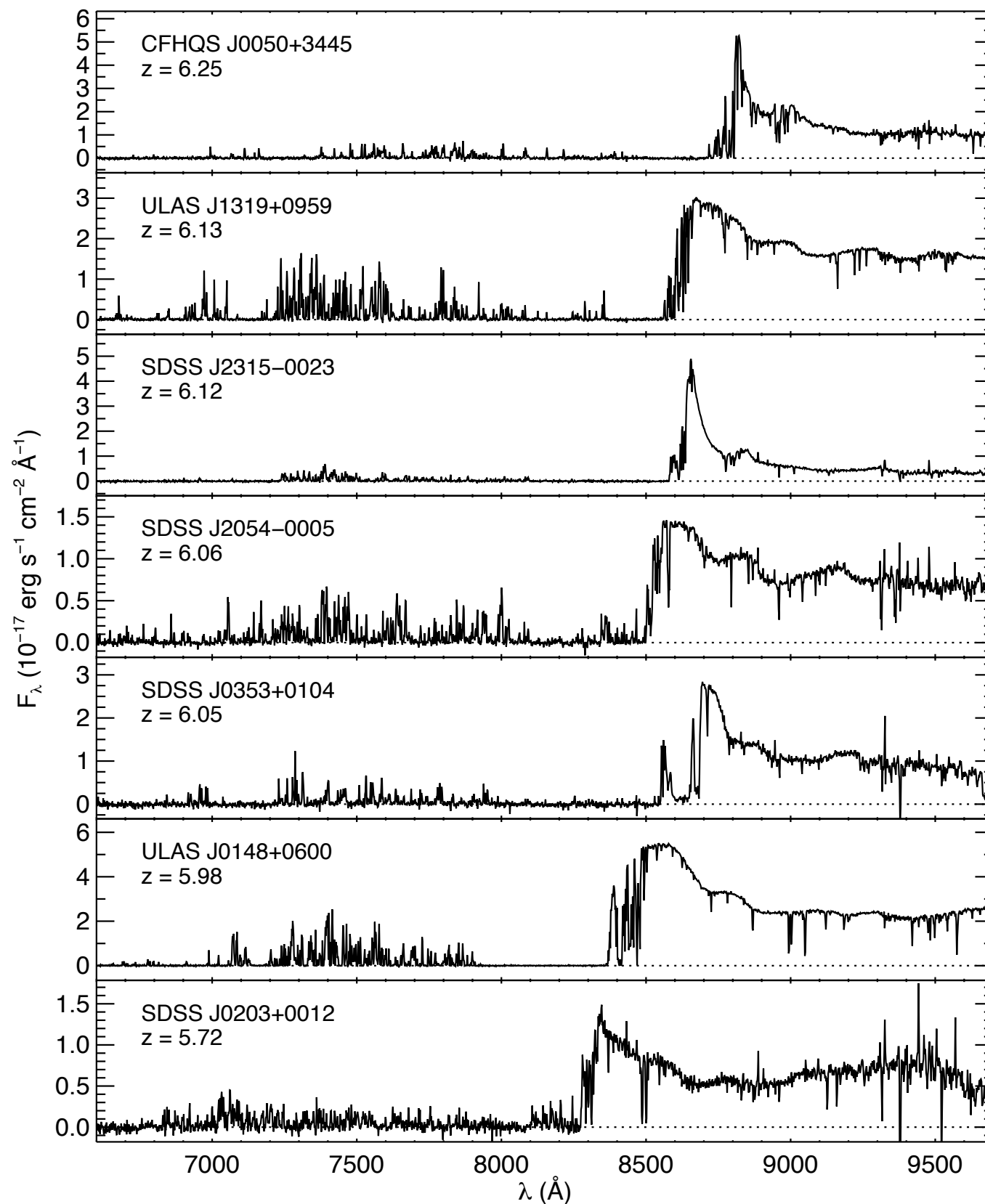
ing, structure, and
even sources of reionization
unknown!

- Focus of this talk:
the $5 < z < 6$ Ly α forest

The Ly α Forest



The High-Redshift Ly α Forest



- Transmitted fraction of flux:

$$F = \exp(-\tau_{\text{Ly}\alpha})$$

- At $z \sim 6$,

$$\tau_{\text{Ly}\alpha} \sim 3 \times 10^5 x_{\text{HI}}$$

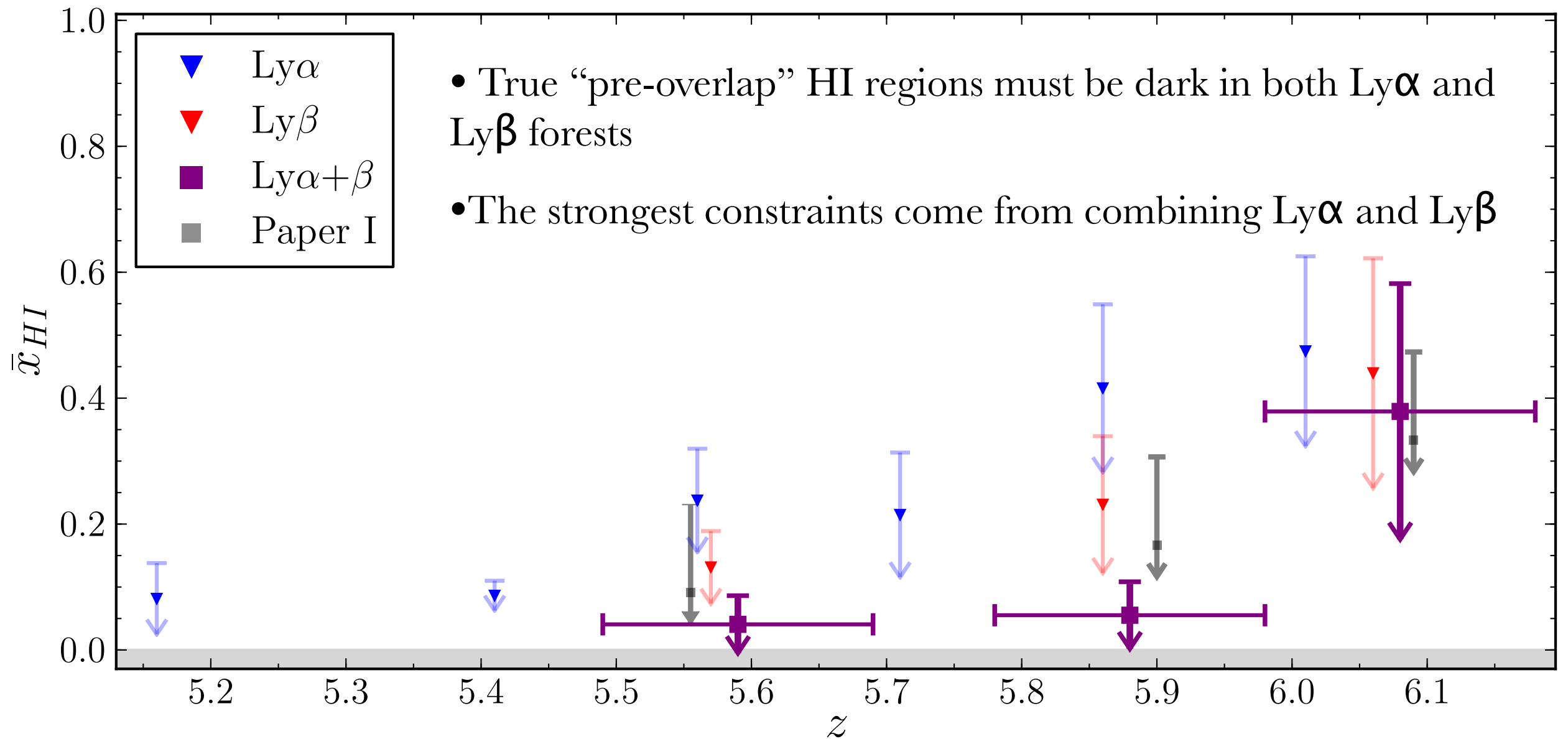
$$\Rightarrow x_{\text{HI}} \sim 2 \times 10^{-5}$$

will block 99% of light in the forest!

- Most $z \sim 6$ segments of the forest show some transmission

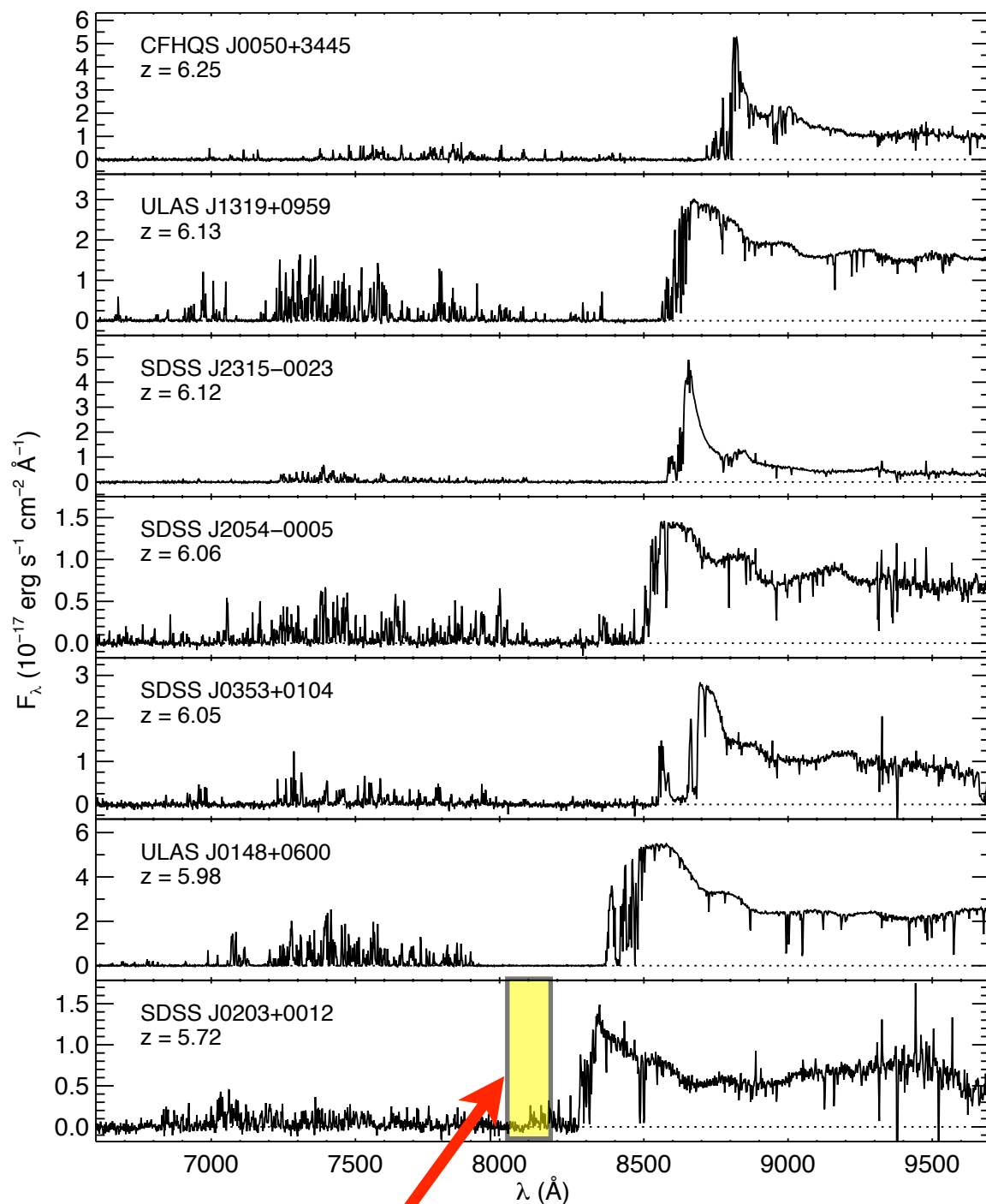
\Rightarrow Reionization largely complete

Ly α Forest Constraints on Reionization

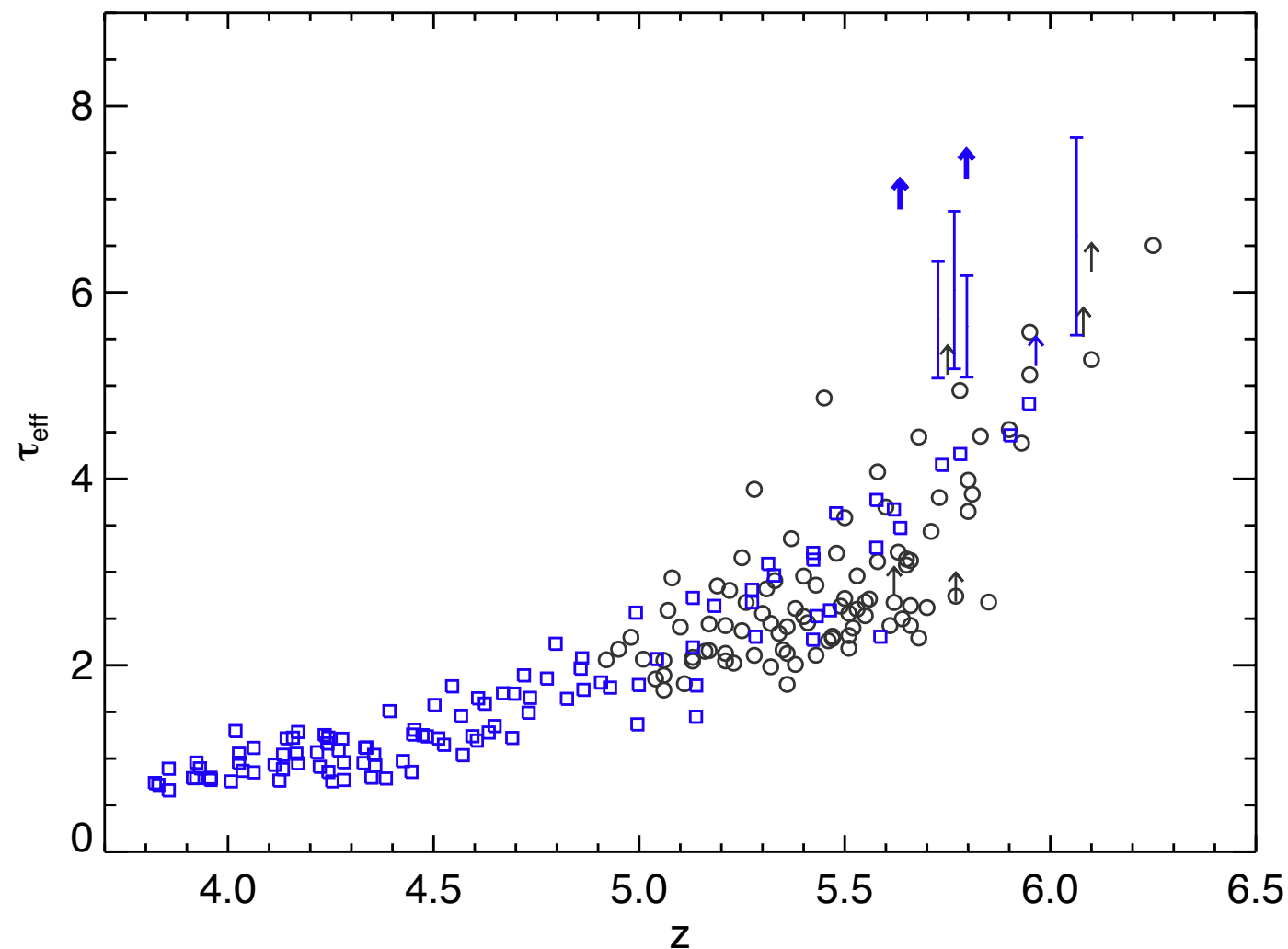


$$x_{\text{HI}} < 0.11 \text{ (0.09) at } z \approx 5.9 \text{ (5.6) } (1\sigma)$$

Quantifying Ly α Forest Opacity



$$L = 50h^{-1} \text{ Mpc}$$



$$\langle F \rangle_L \equiv \exp(-\tau_{\text{eff}})$$

(F is continuum normalized)

Dispersion in τ_{eff}

- Note evolution in both mean *and* dispersion

$$\tau_{\text{Ly}\alpha} \propto n_{\text{HI}} \propto \frac{\alpha_A n_e n_{\text{HII}}}{\Gamma}$$

$$\tau_{\text{Ly}\alpha} \propto \frac{T^{-0.7} \Delta_b^2}{\Gamma}$$

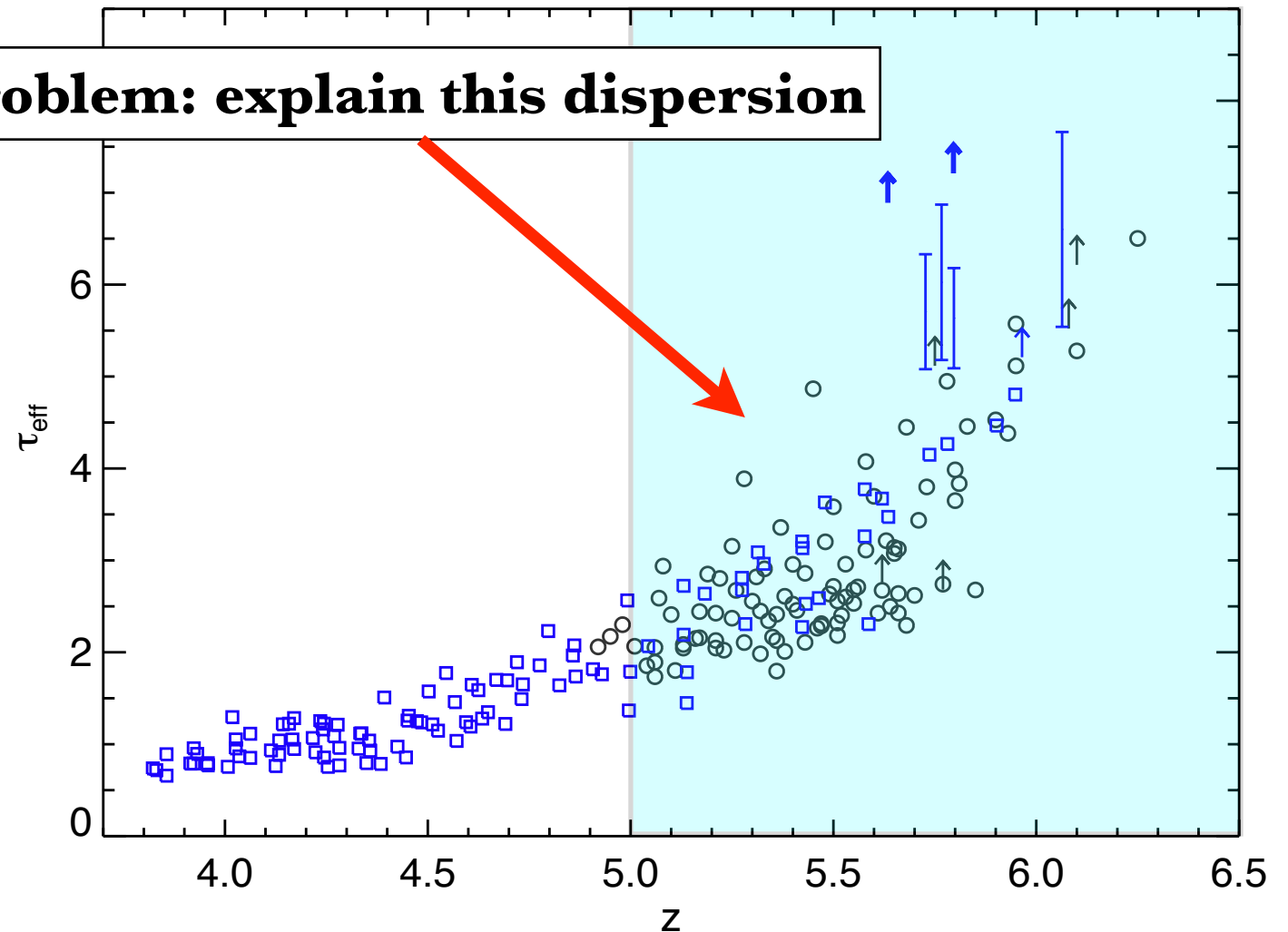
Density fluctuations

$$\Gamma \propto \int_{13.6\text{eV}}^{\infty} \frac{d\nu}{\nu} J_{\nu}(\nu) \sigma_H(\nu)$$

Temperature fluctuations

Ionizing background fluctuations

Problem: explain this dispersion

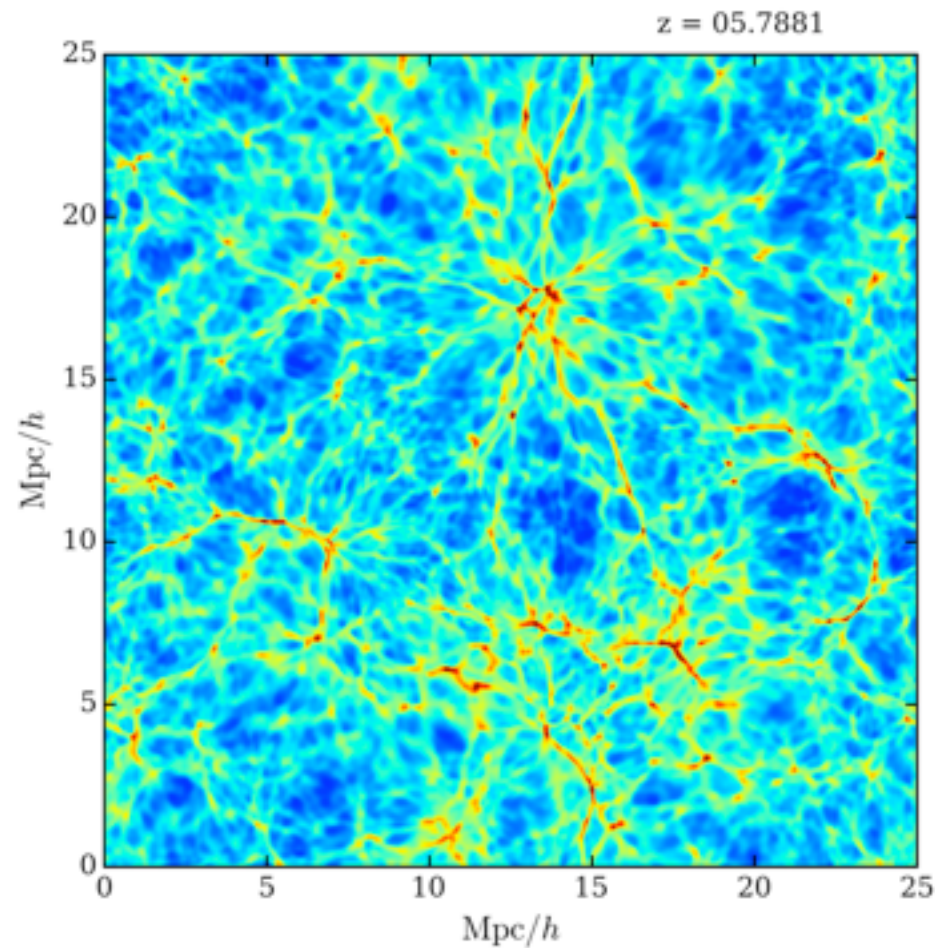


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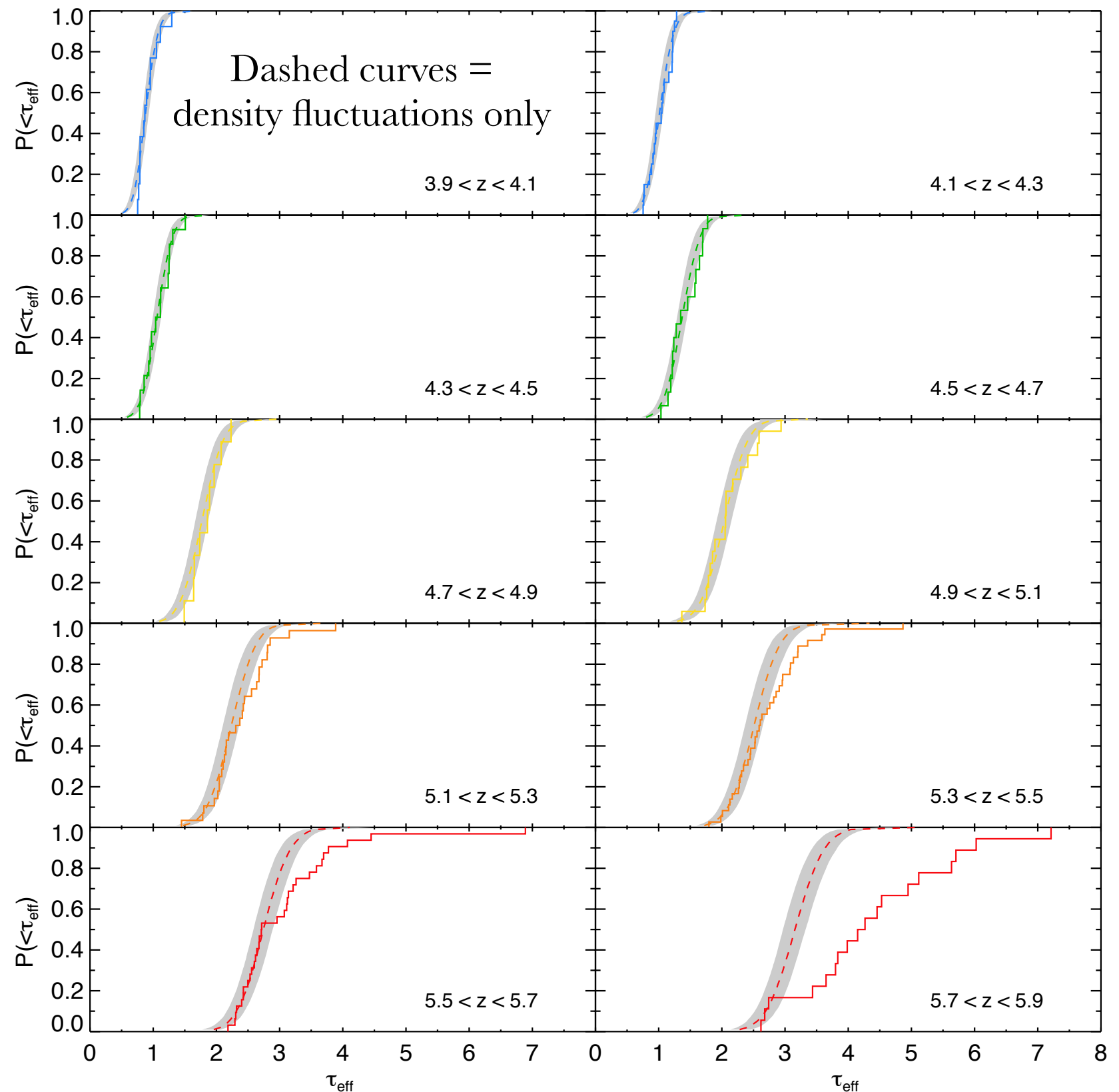
(F is continuum normalized)

$$\tau_{\text{Ly}\alpha} \propto \frac{T^{-0.7} \Delta_b^2}{\Gamma}$$

IGM Density Fluctuations are not Enough



Cosmological
hydro simulation

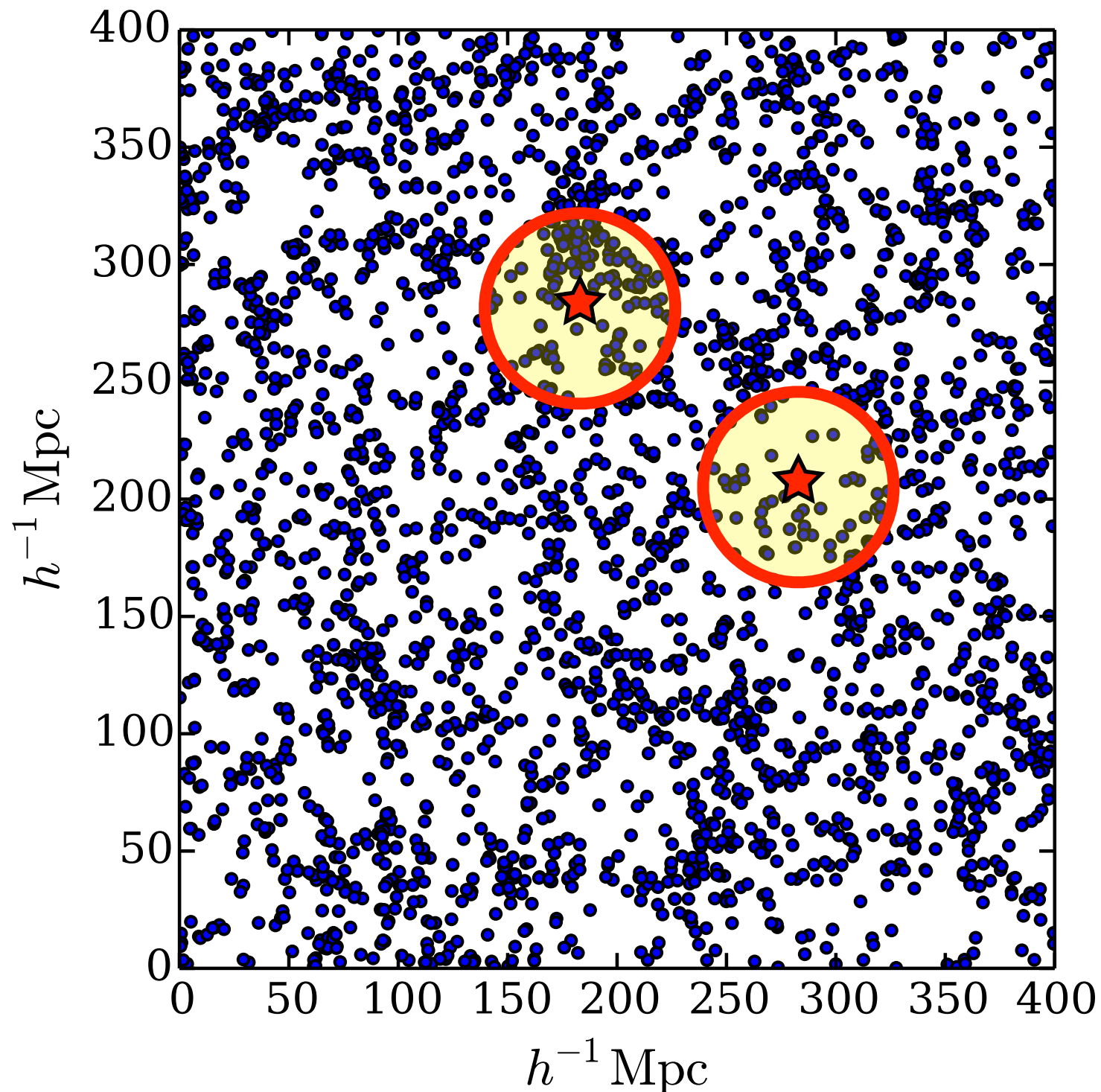


$$\tau_{\text{Ly}\alpha} \propto \frac{T^{-0.7} \Delta_b^2}{\Gamma}$$

From Becker et al. (2015)

Inhomogeneous Ionizing Background

(Cartoon source distribution)



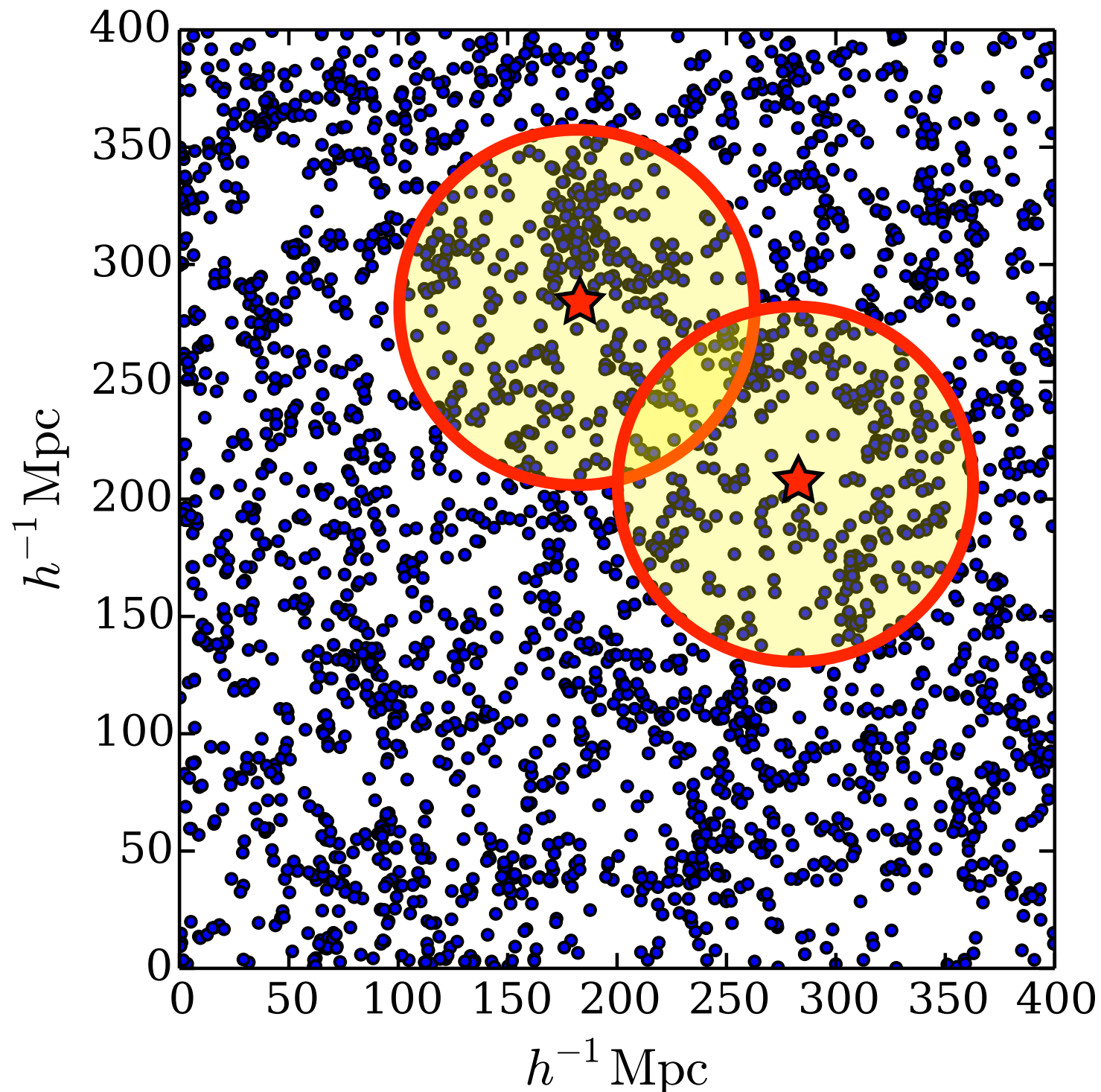
Ionizing background set by:

- Abundance and clustering of sources
- Mean free path (MFP) of photons
- At $z=5-6$, MFP set by absorbers with $\Delta_b \sim 100$
- Larger MFP = smaller background fluctuations

$$\tau_{\text{Ly}\alpha} \propto \frac{T^{-0.7} \Delta_b^2}{\Gamma}$$

Inhomogeneous Ionizing Background

(Cartoon source distribution)

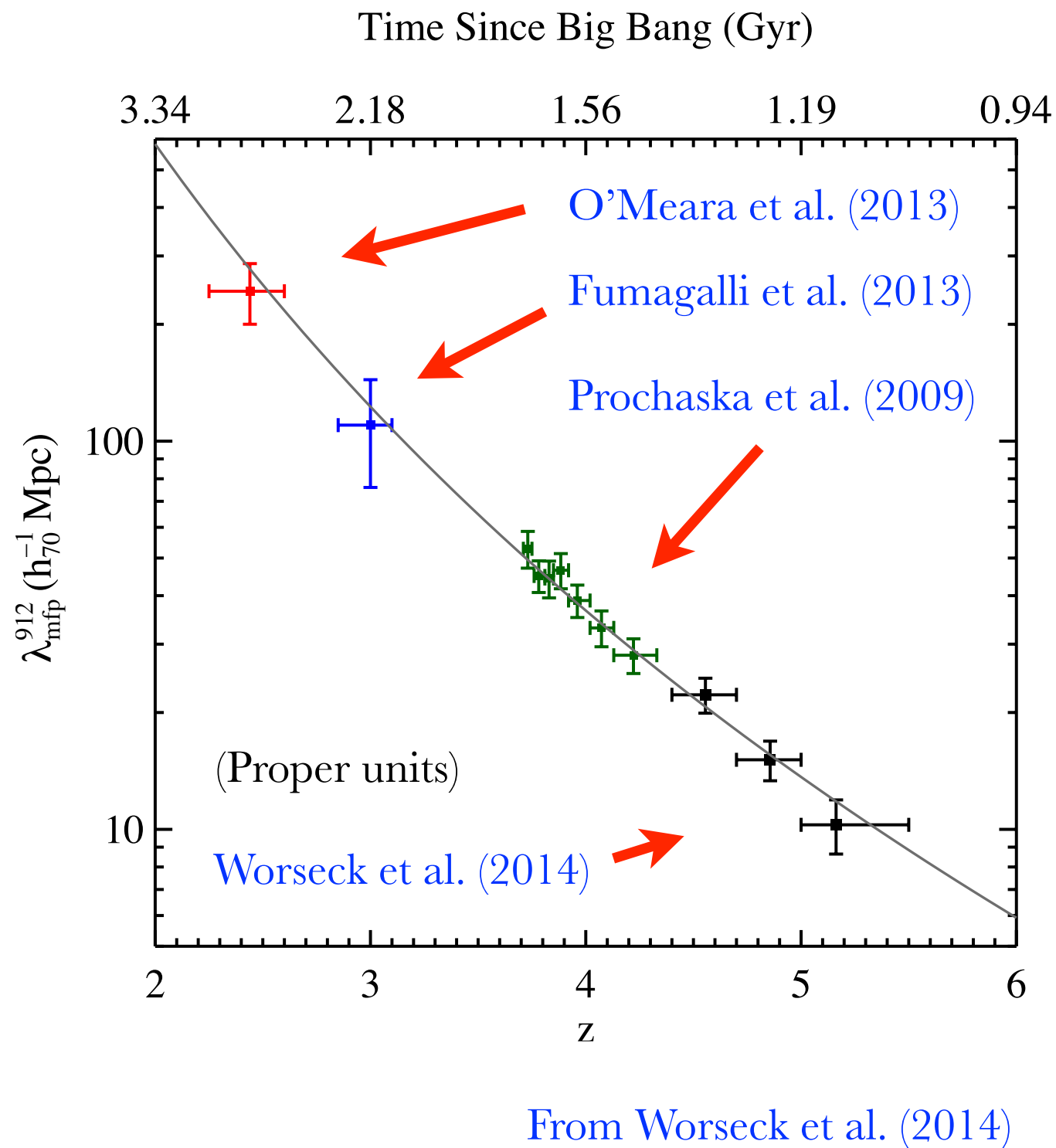


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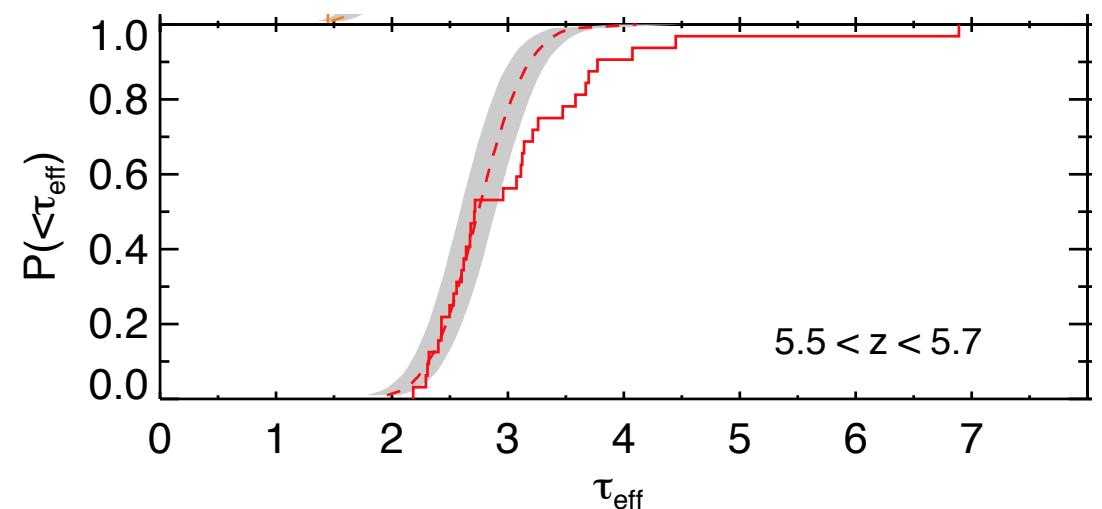
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Mean Free Path

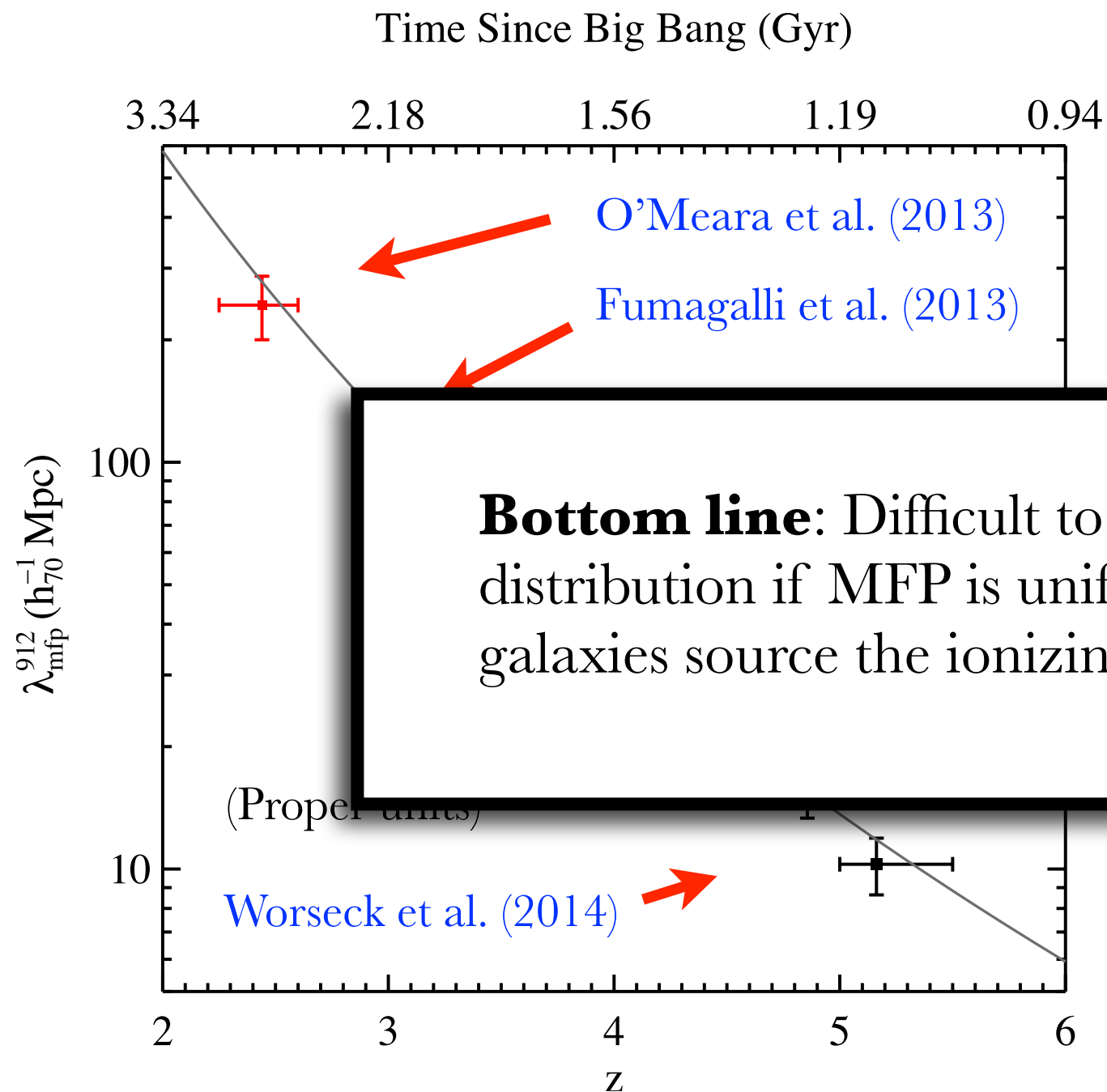


- MFP = 90 comoving Mpc at $z = 5.2$
- **Extrapolating to $z = 5.6$ yields MFP = 50 comoving Mpc**
- If MFP is uniform, no significant τ_{eff} fluctuations,
- True even for much smaller MFP (Davies & Furlanetto 2015)



$$\tau_{\text{Ly}\alpha} \propto \frac{T^{-0.7} \Delta_b^2}{\Gamma}$$

Mean Free Path

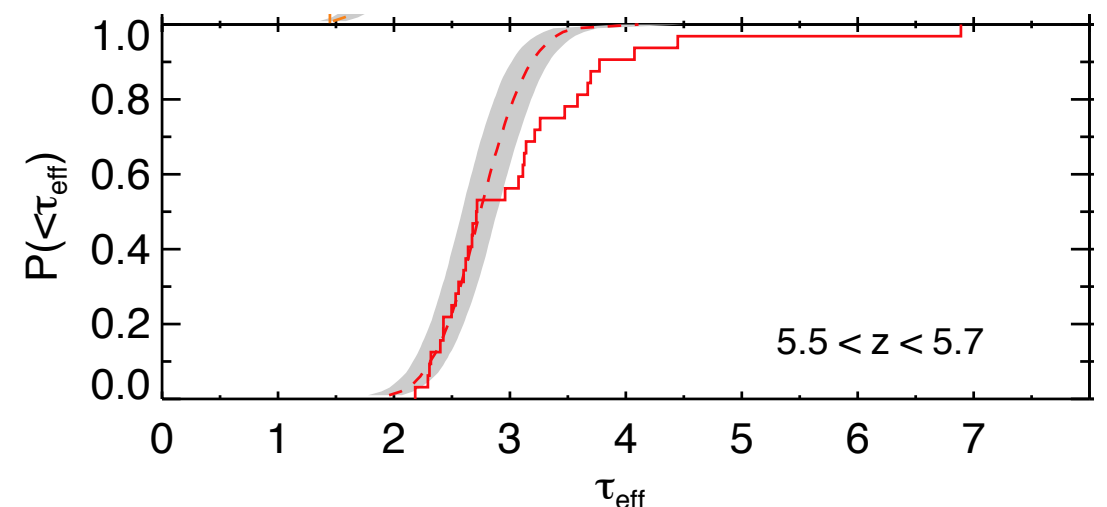


- MFP = 90 comoving Mpc at $z = 5.2$
- **Extrapolating to $z = 5.6$**
- **90 comoving Mpc**

no significant
with smaller MFP

(Davies & Furlanetto 2015)

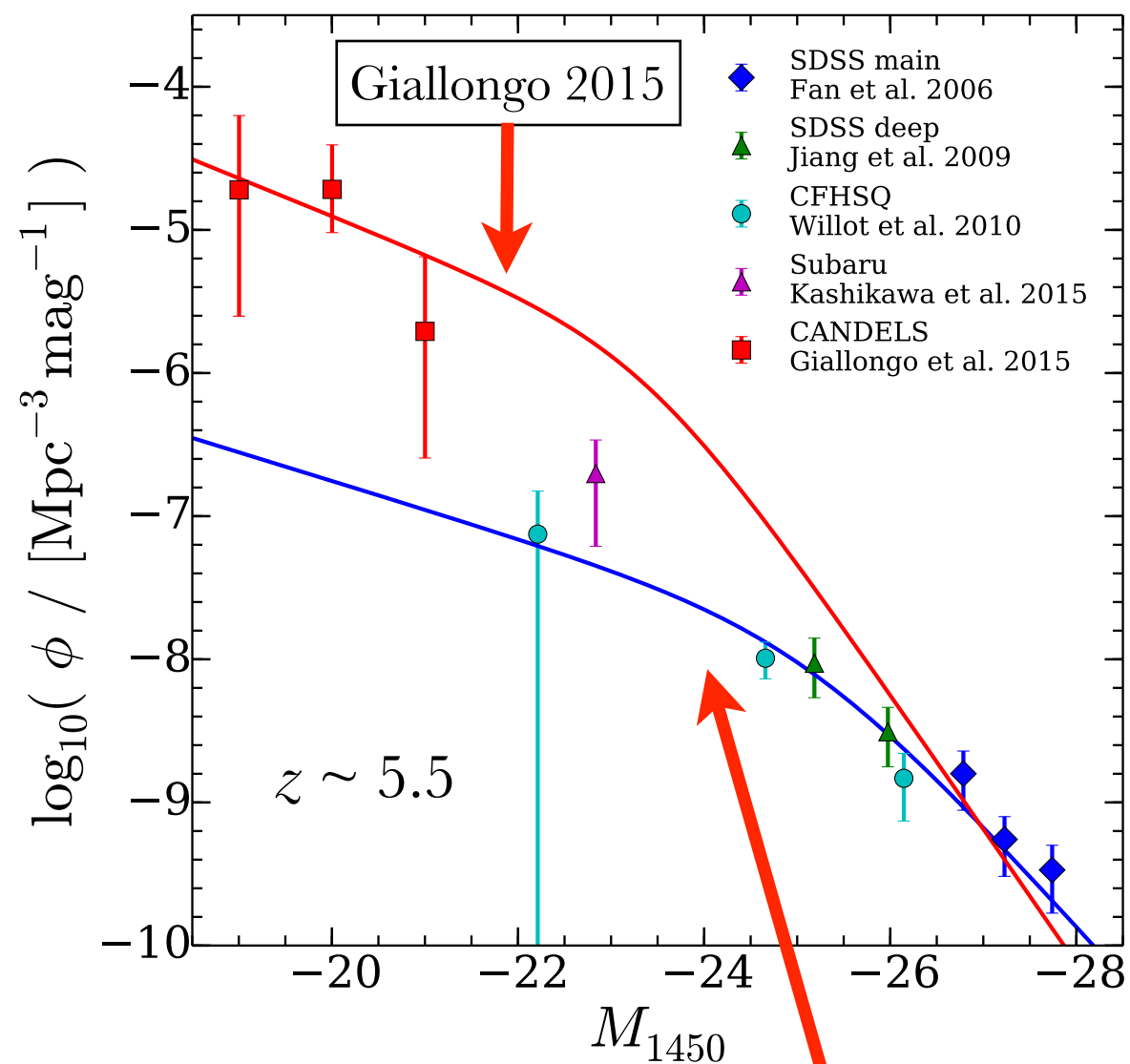
From Worseck et al. (2014)



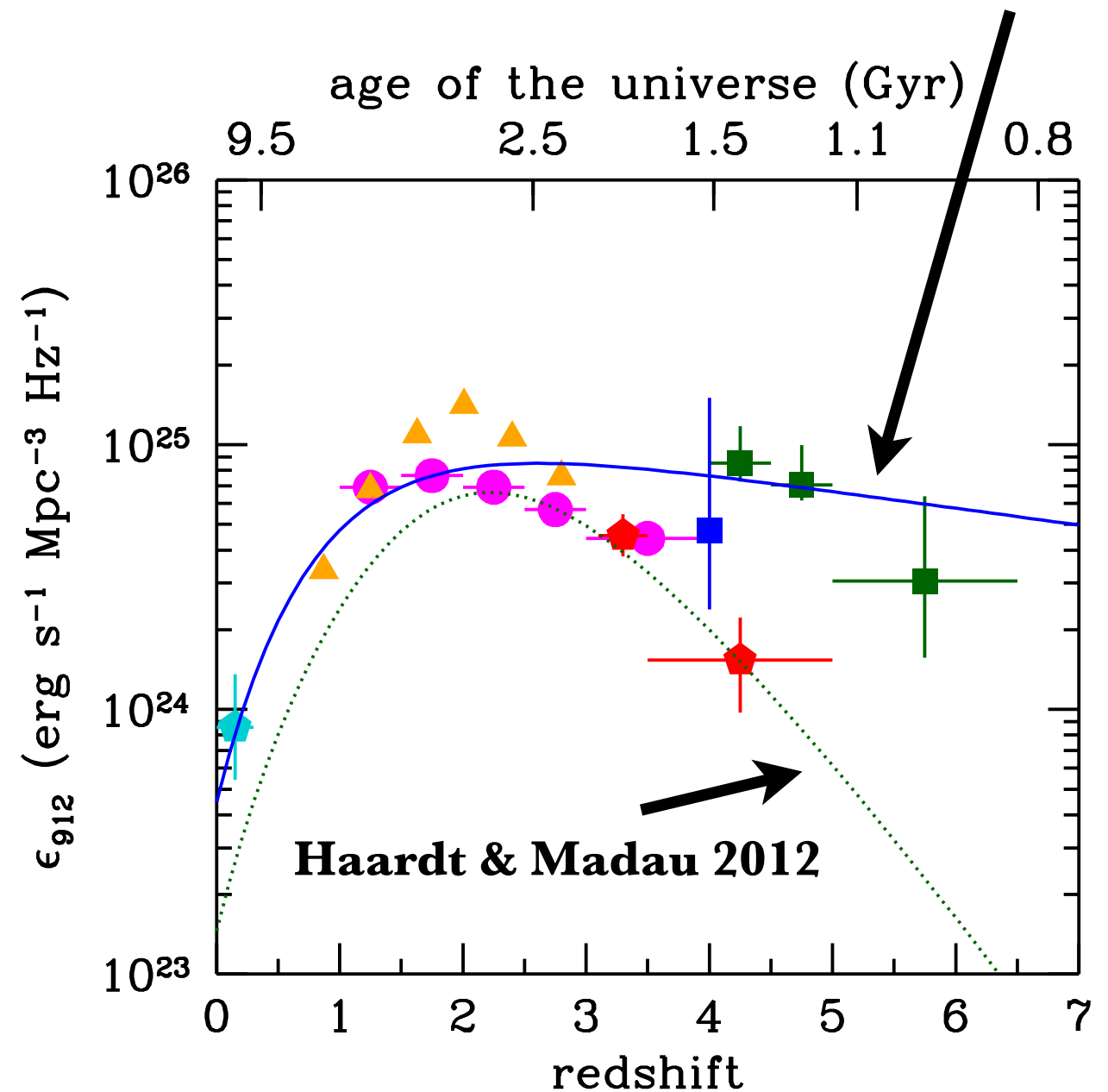
$$\tau_{\text{Ly}\alpha} \propto \frac{T^{-0.7} \Delta_b^2}{\Gamma}$$

(1) Rare Sources (Quasars)

- [Chardin et al. 2015](#): explain opacity fluctuation excess if $\sim 1/2$ the background is from 2 sources per $(100 h^{-1} \text{Mpc})^3$



Madau & Haardt 2015: “Could quasars do it all?”



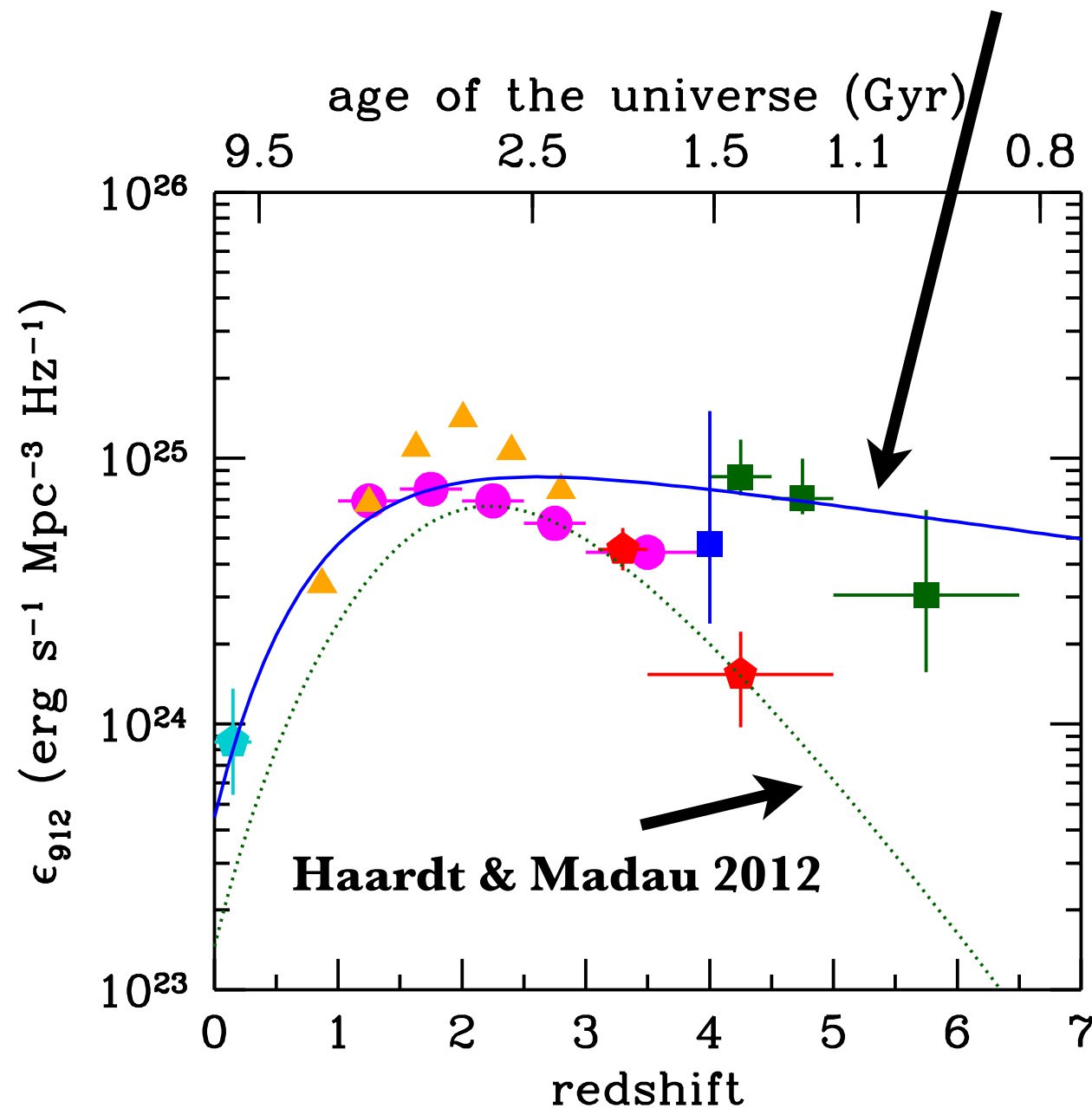
From Madau & Haardt (2015)

$$\tau_{\text{Ly}\alpha} \propto \frac{T^{-0.7} \Delta_b^2}{\Gamma}$$

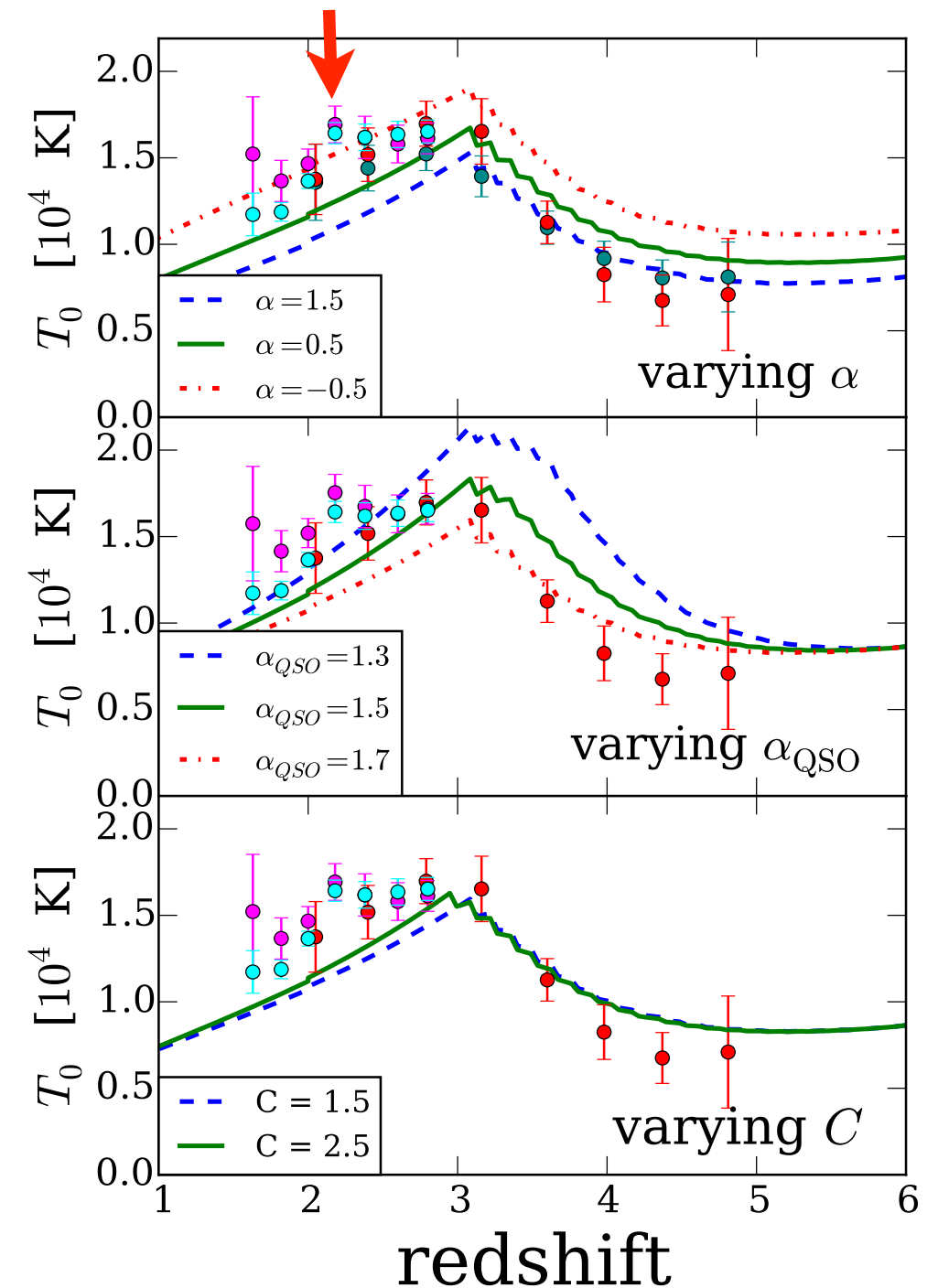
Previous measurements

(1) Rare Sources (Quasars)

Madau & Haardt: Helium Reionizes by $z = 4$



Measurements from Becker et al. (2011)
and Boera et al. (2014)



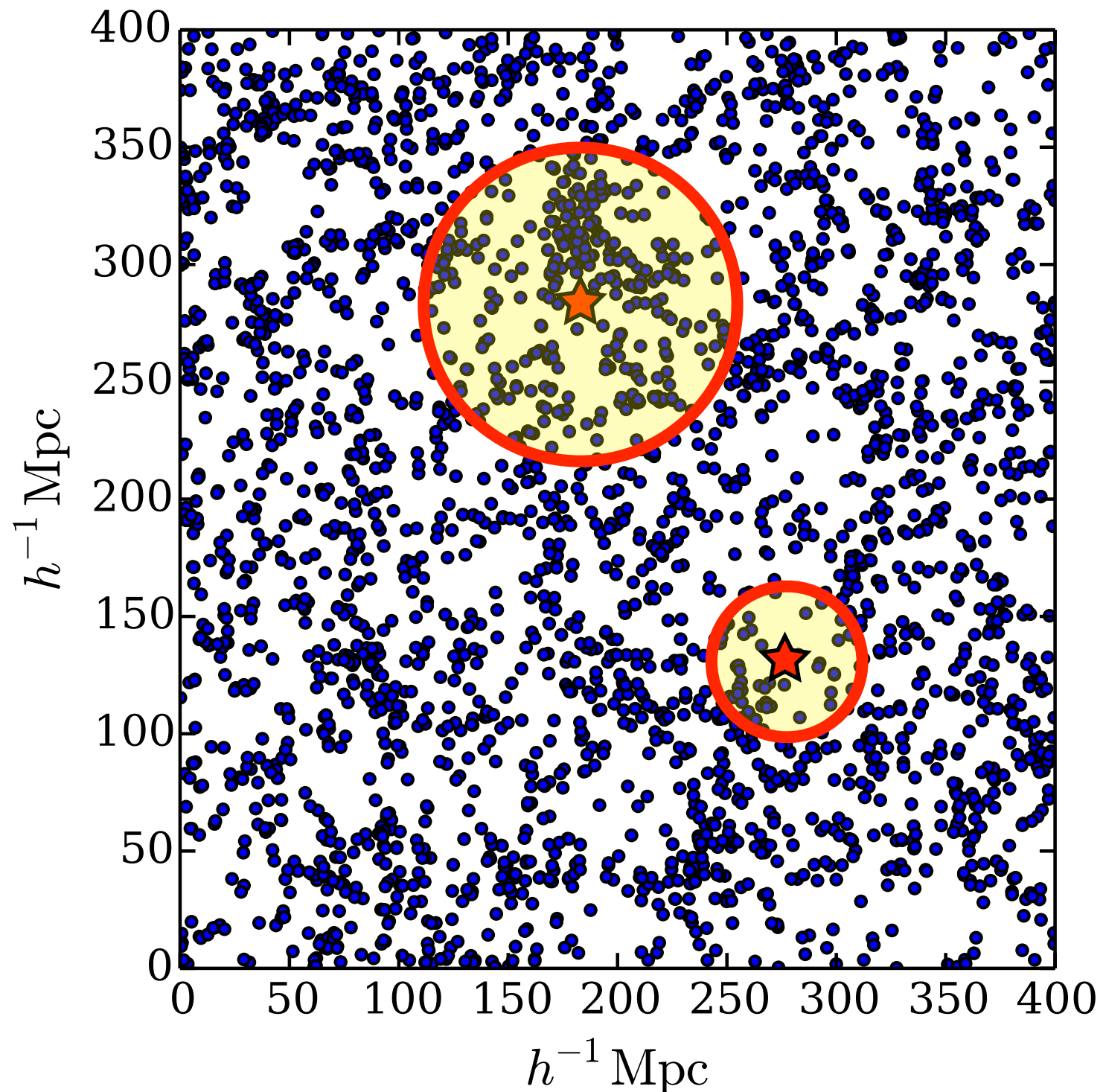
$$\tau_{\text{Ly}\alpha} \propto \frac{T^{-0.7} \Delta_b^2}{\Gamma}$$

From Upton Sanderbeck, D'Aloisio & McQuinn (2015)

(2) Spatial Variations in Mean Free Path

- MFP may vary over large scales
([Davies & Furlanetto 2015](#))
- Local amplitude of ionizing background sets ionization state of absorbers ([Furlanetto & Oh 2005](#); [McQuinn et al. 2011](#))
- **Note: not necessarily a signature of reionization!**
- Spatially varying MFP even in post-reionization IGM

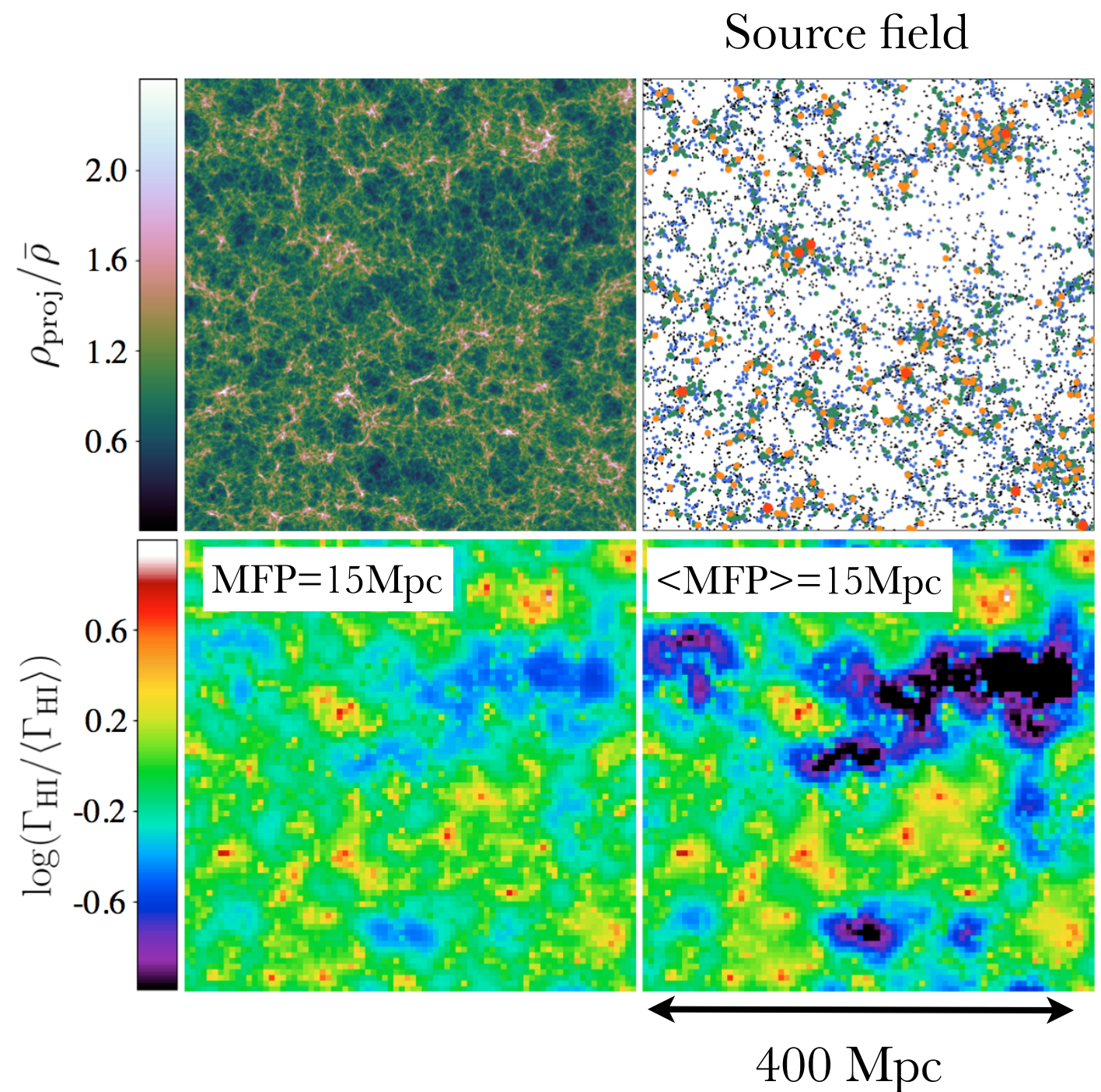
(Cartoon source distribution)



$$\tau_{\text{Ly}\alpha} \propto \frac{T^{-0.7} \Delta_b^2}{\Gamma}$$

(2) Spatial Variations in Mean Free Path

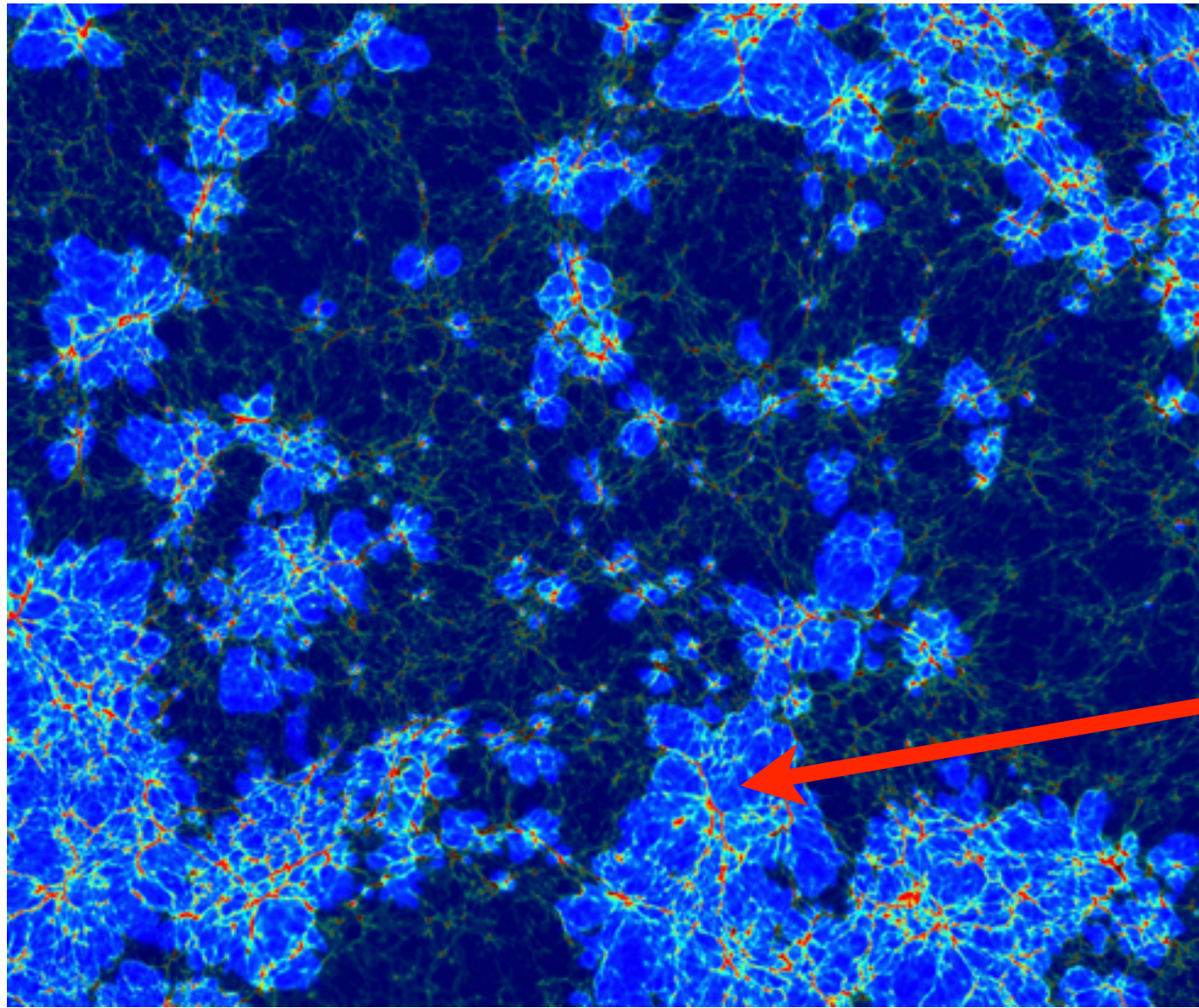
- Modeled self-consistently in [Davies & Furlanetto \(2015\)](#)
- **Under-dense voids are most opaque (largest τ_{eff})!**
- Fully account for width of distribution at $z = 5.6$ with average MFP ~ 15 Mpc, factor of a few fluctuations



$$\tau_{\text{Ly}\alpha} \propto \frac{T^{-0.7} \Delta_b^2}{\Gamma}$$

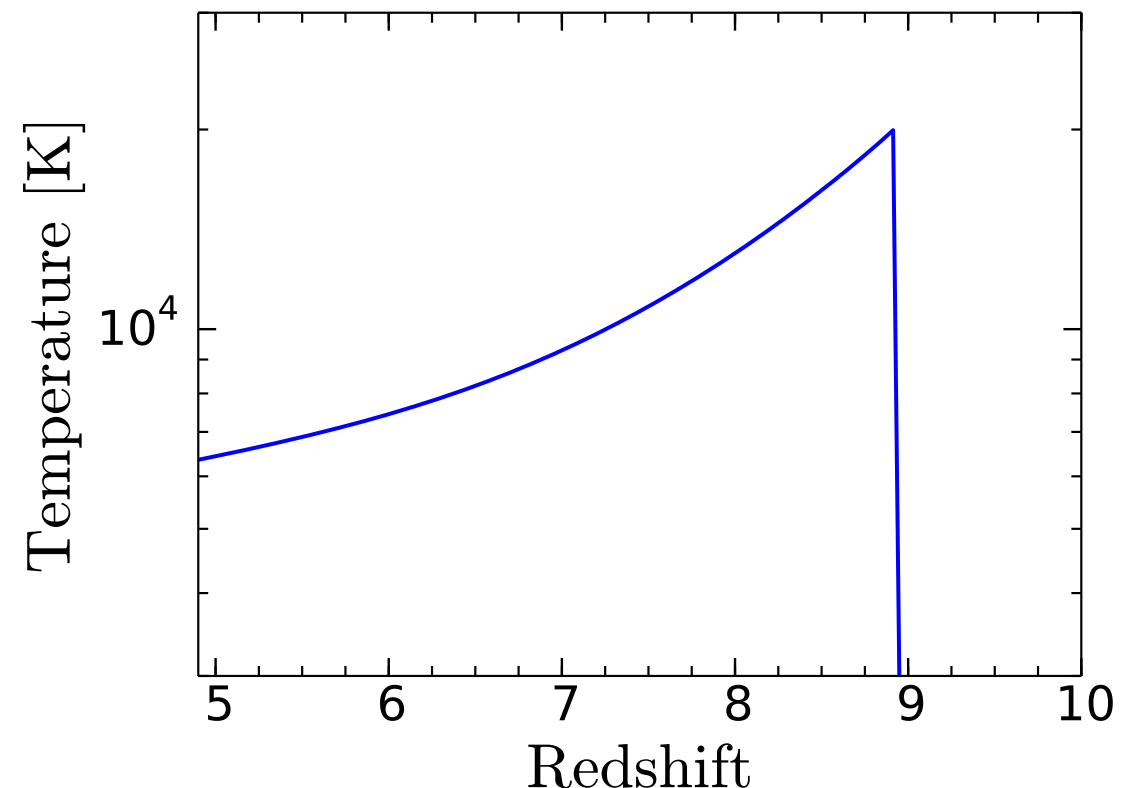
From Davies & Furlanetto (2015)

(3) Relic Temperature Fluctuations from Reionization



*Image by Hyunbae Park, CoDa Simulation (PI: P.R. Shapiro)

- Reionization heats IGM to $T_{\text{reion}} = 20,000 - 30,000$ K
- Heating processes: photoheating
- Cooling processes: adiabatic expansion, Compton, recombination, free-free



Primary: rec. coefficient; **Secondary:** thermal width and Jeans smoothing.

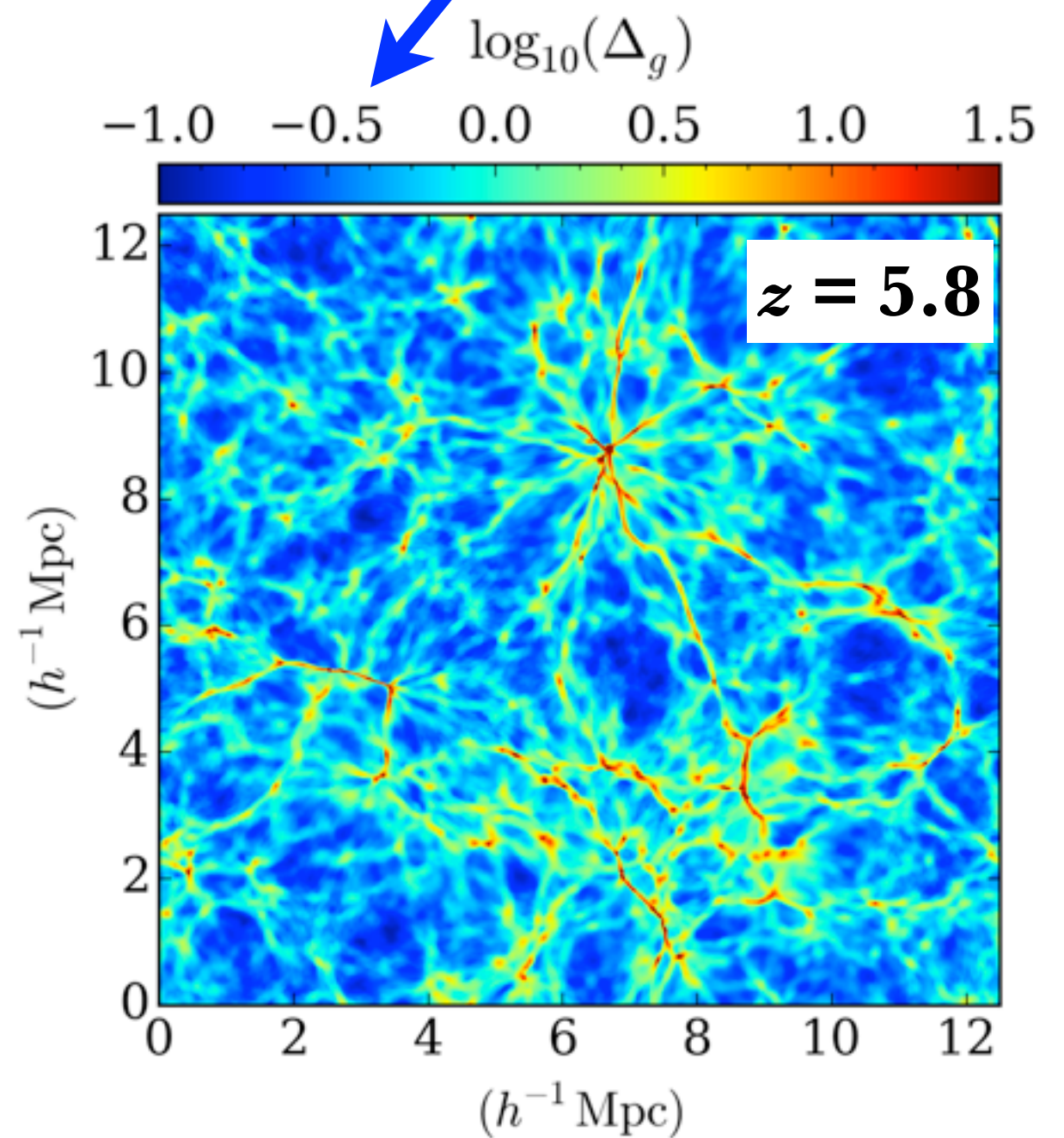
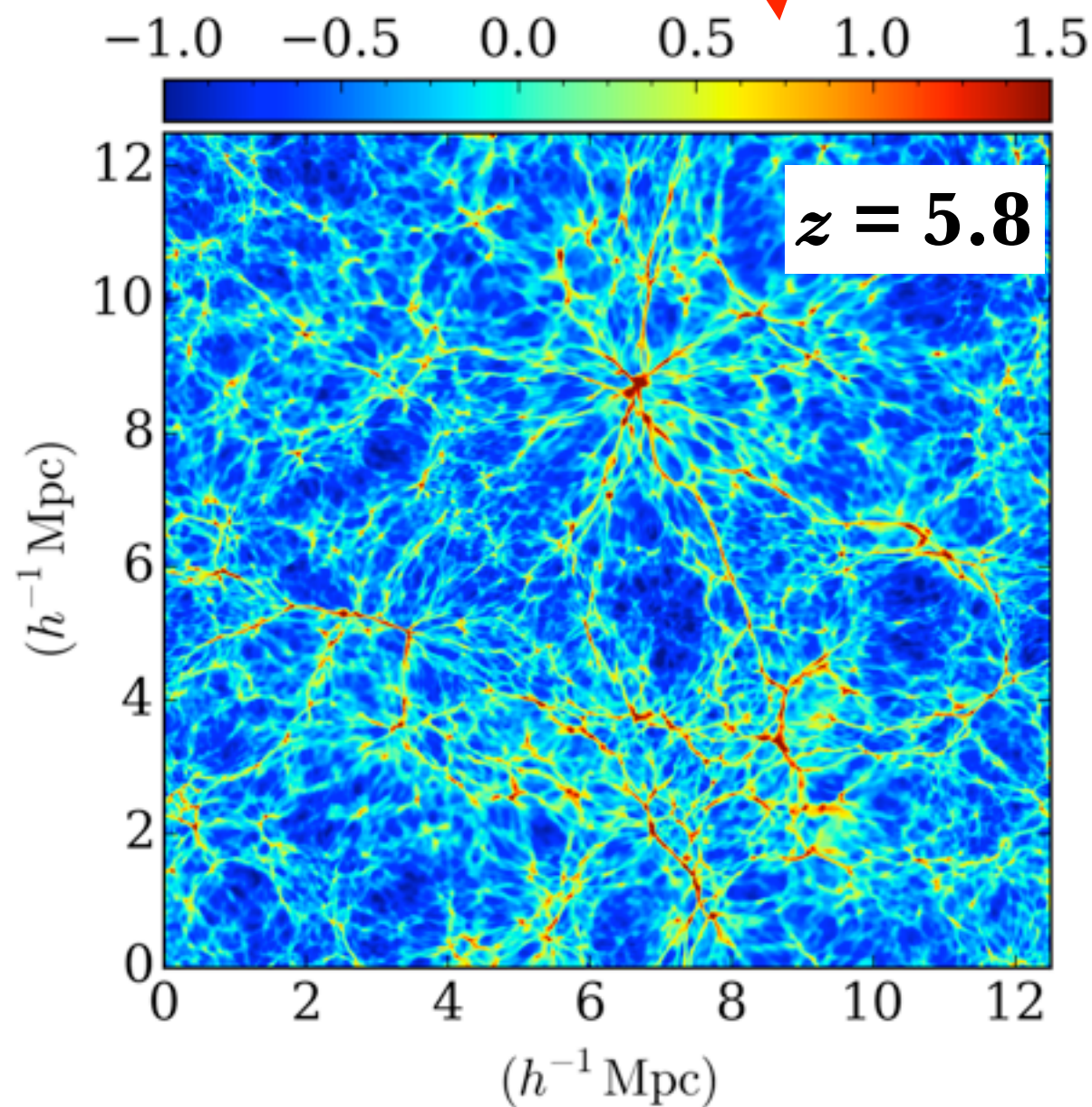
$$\tau_{\text{Ly}\alpha} \propto \frac{T^{-0.7} \Delta_b^2}{\Gamma}$$

D'Aloisio, McQuinn & Trac 2015. See also Upton Sanderbeck, D'Aloisio & McQuinn (2015); Trac et al. (2008); Cen et al. (2009); Furlanetto & Oh (2009); Lidz & Malloy (2014)

Hydrodynamical Simulations

$$z_{\text{reion}} = \{6, 6.5, 7, 7.5, 8, 8.5, 9, 10, 11, 12\}$$

$$\log_{10}(\Delta_g)$$



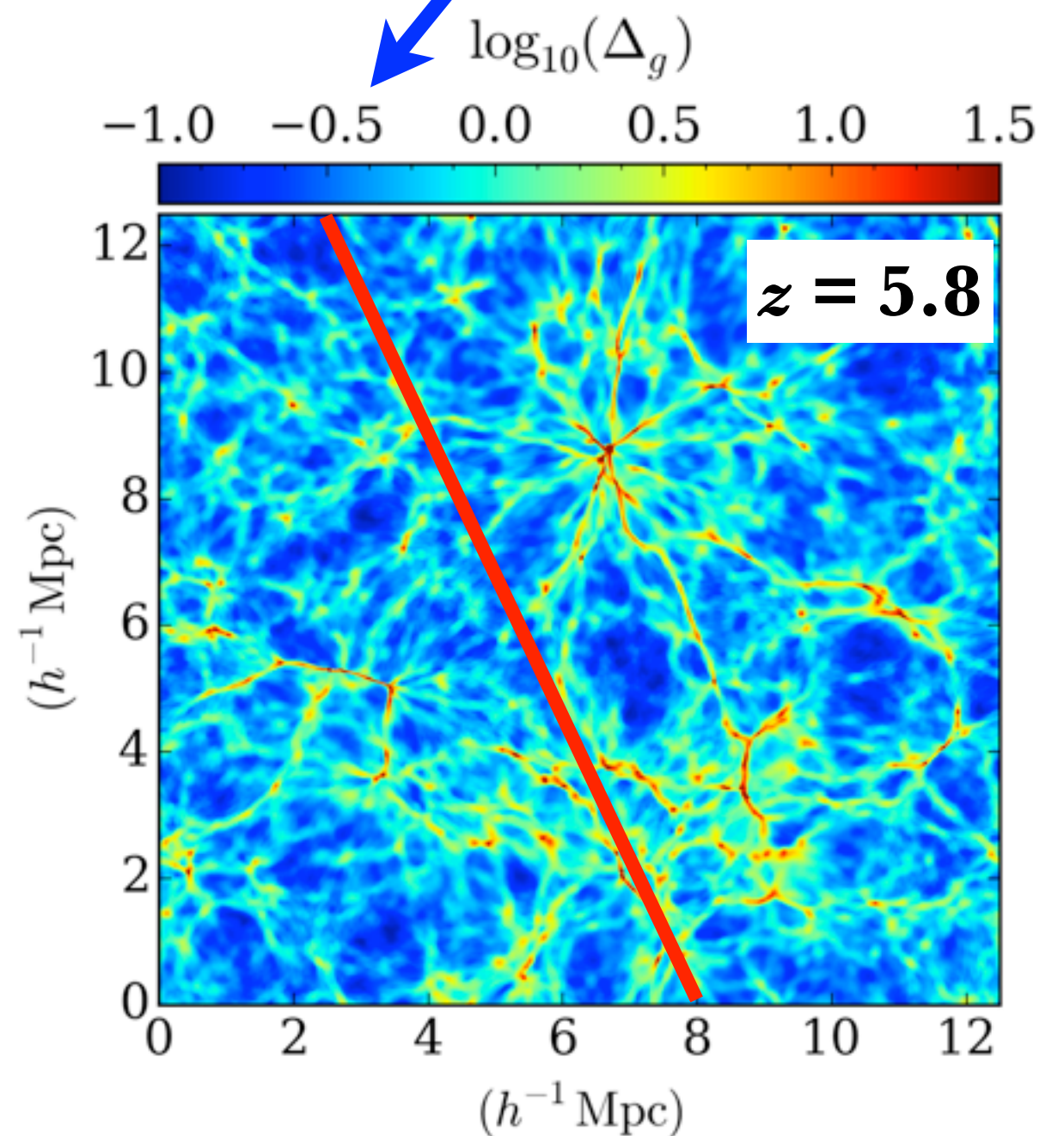
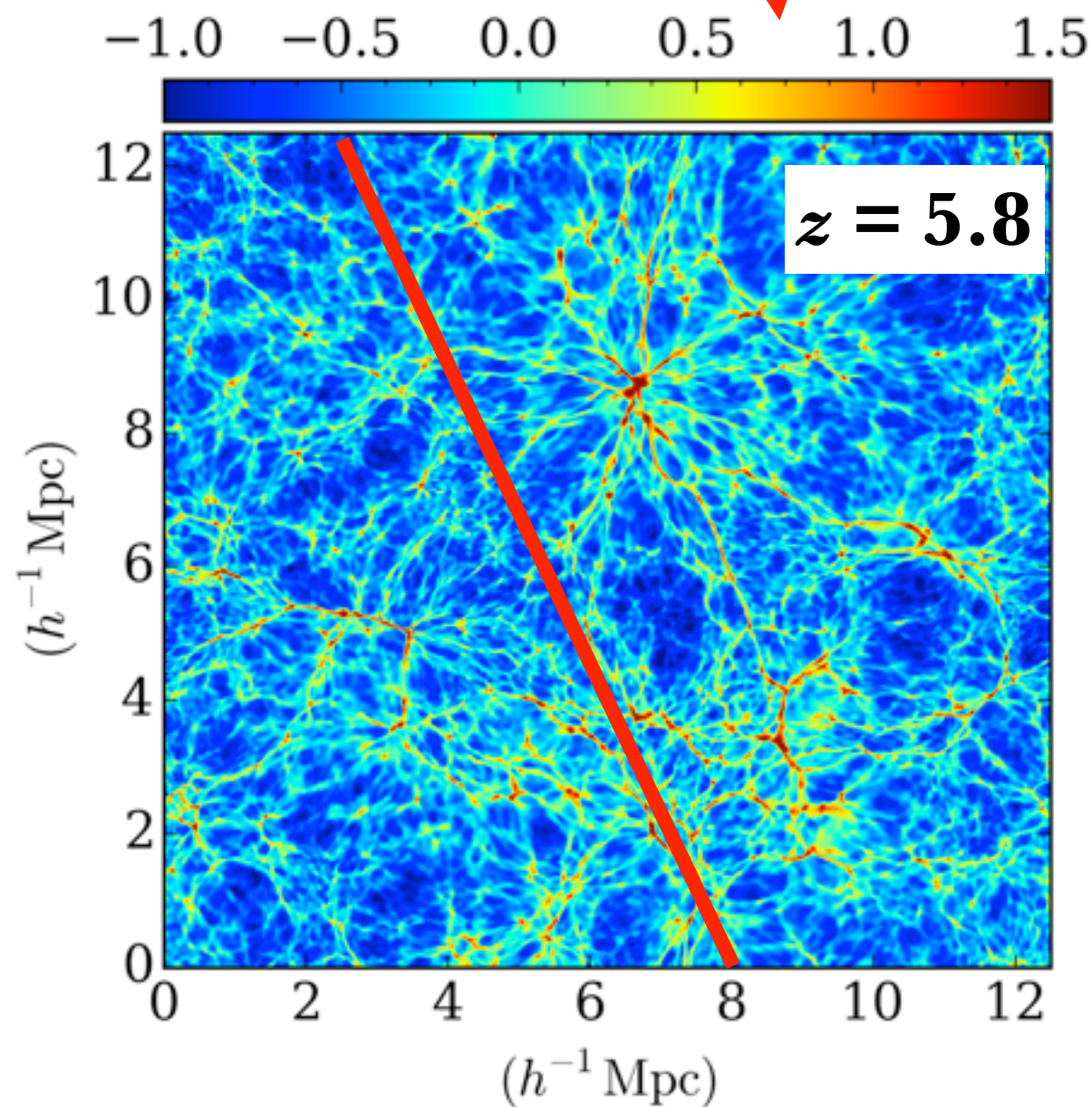
$$\tau_{\text{Ly}\alpha} \propto \frac{T^{-0.7} \Delta_b^2}{\Gamma}$$

$$N = 1024^3, \quad L = 12.5 \, h^{-1} \text{ Mpc}$$

Hydrodynamical Simulations

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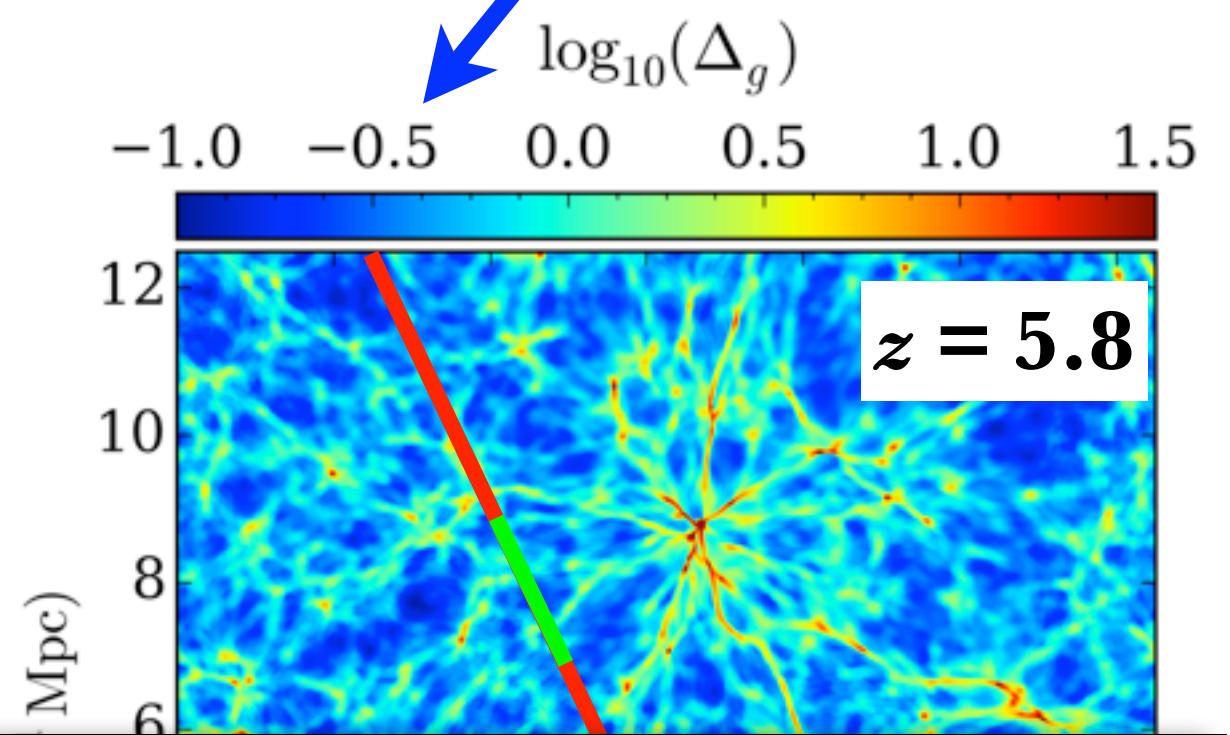
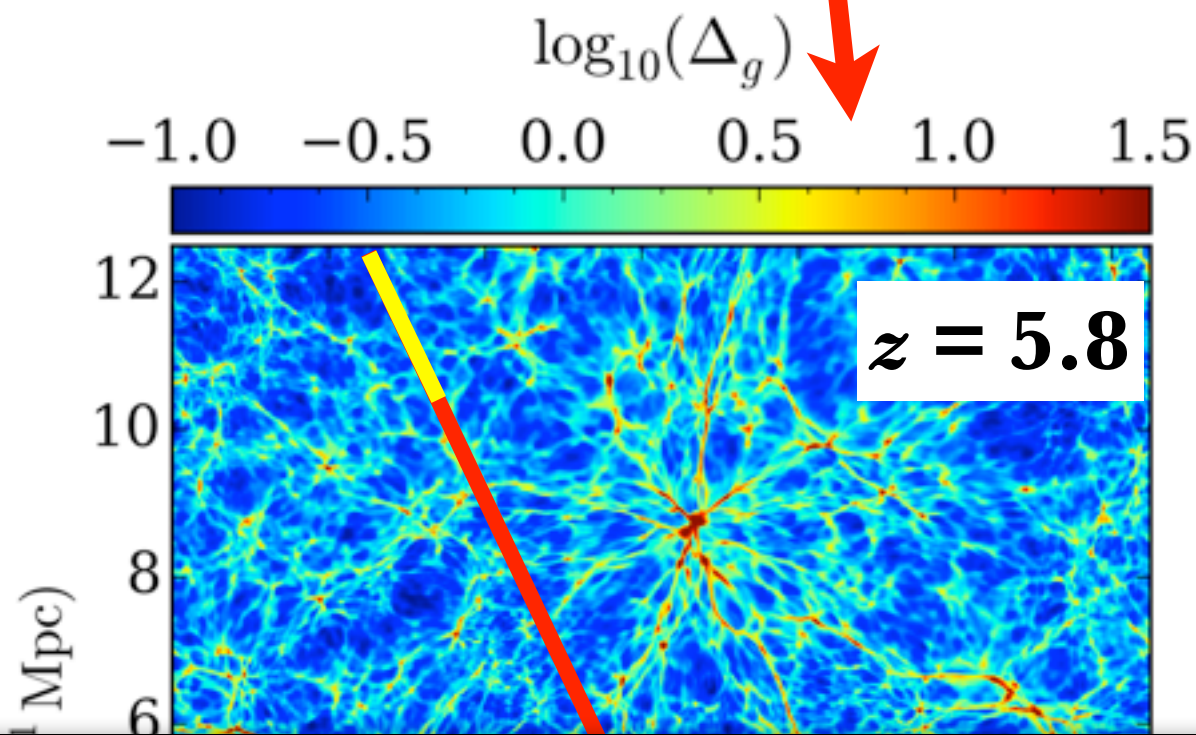


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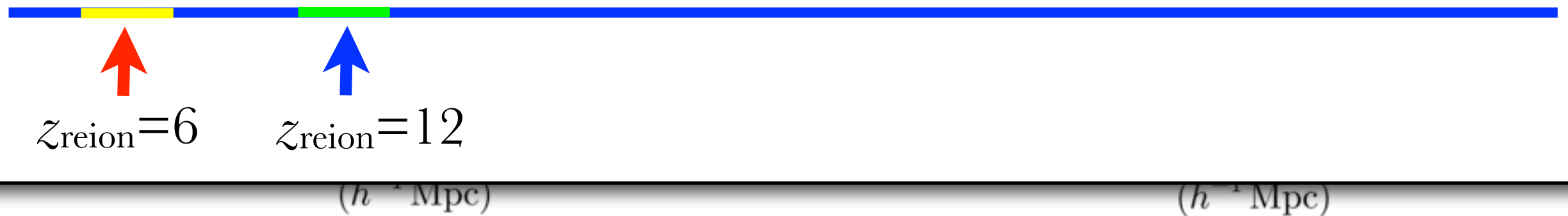
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Hydrodynamical Simulations

$$z_{\text{reion}} = \{6, 6.5, 7, 7.5, 8, 8.5, 9, 10, 11, 12\}$$



Mock Ly α forest spectrum

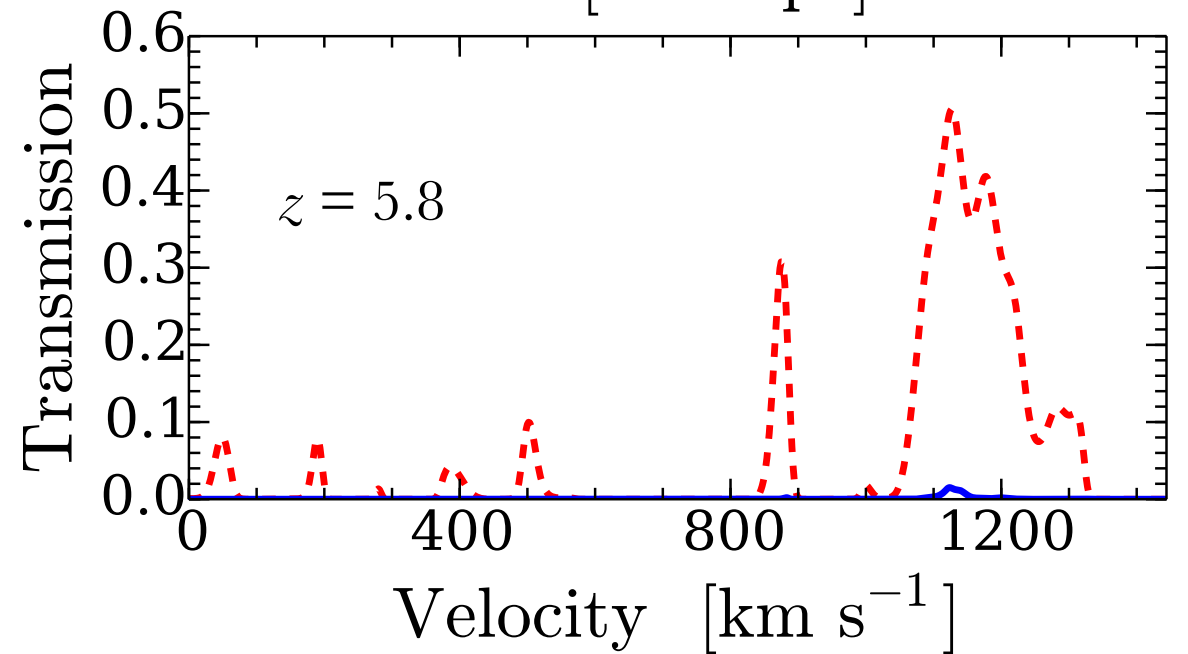
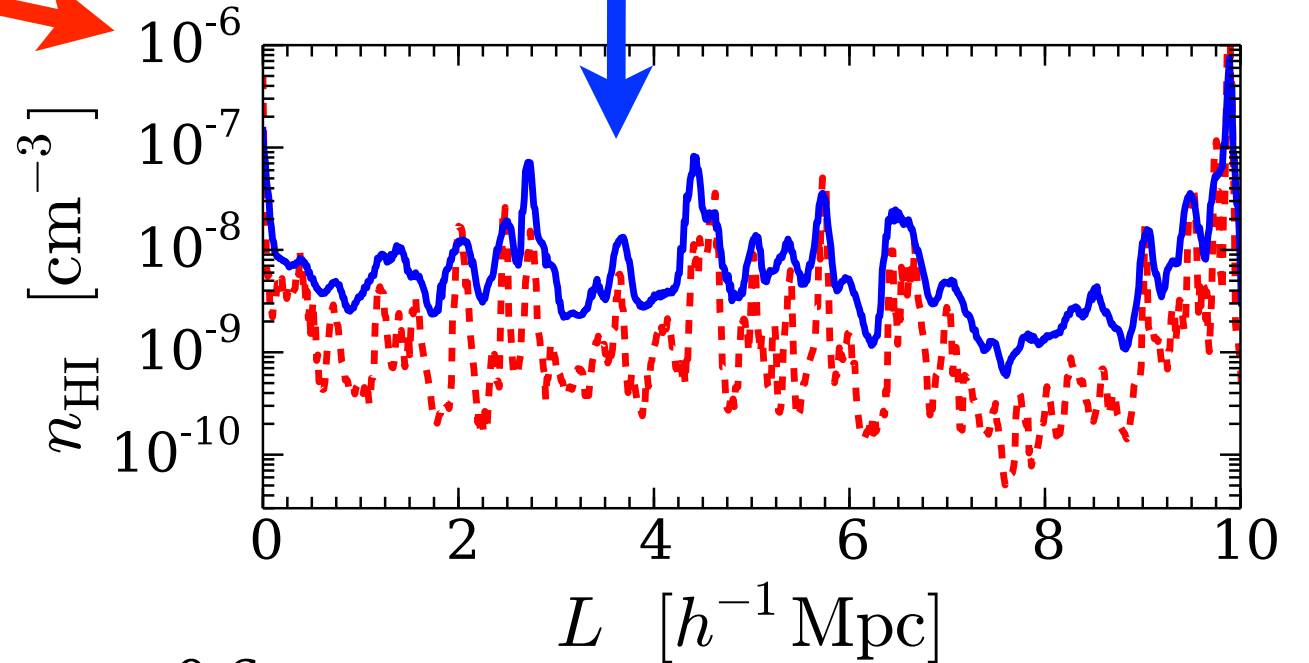
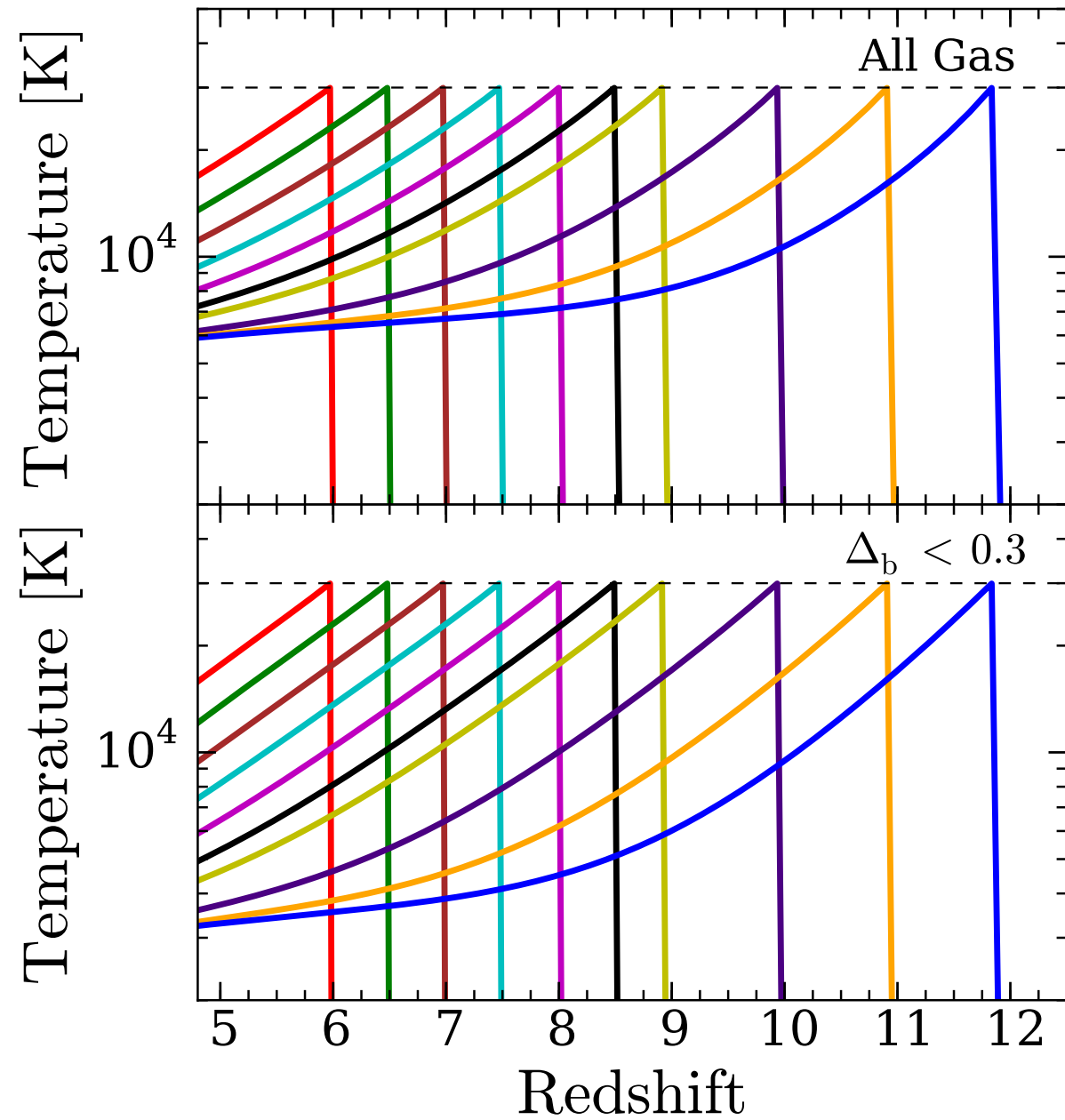


$$\tau_{\text{Ly}\alpha} \propto \frac{T^{-0.7} \Delta_b^2}{\Gamma}$$

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Effect of Temperature on Ly α Opacity

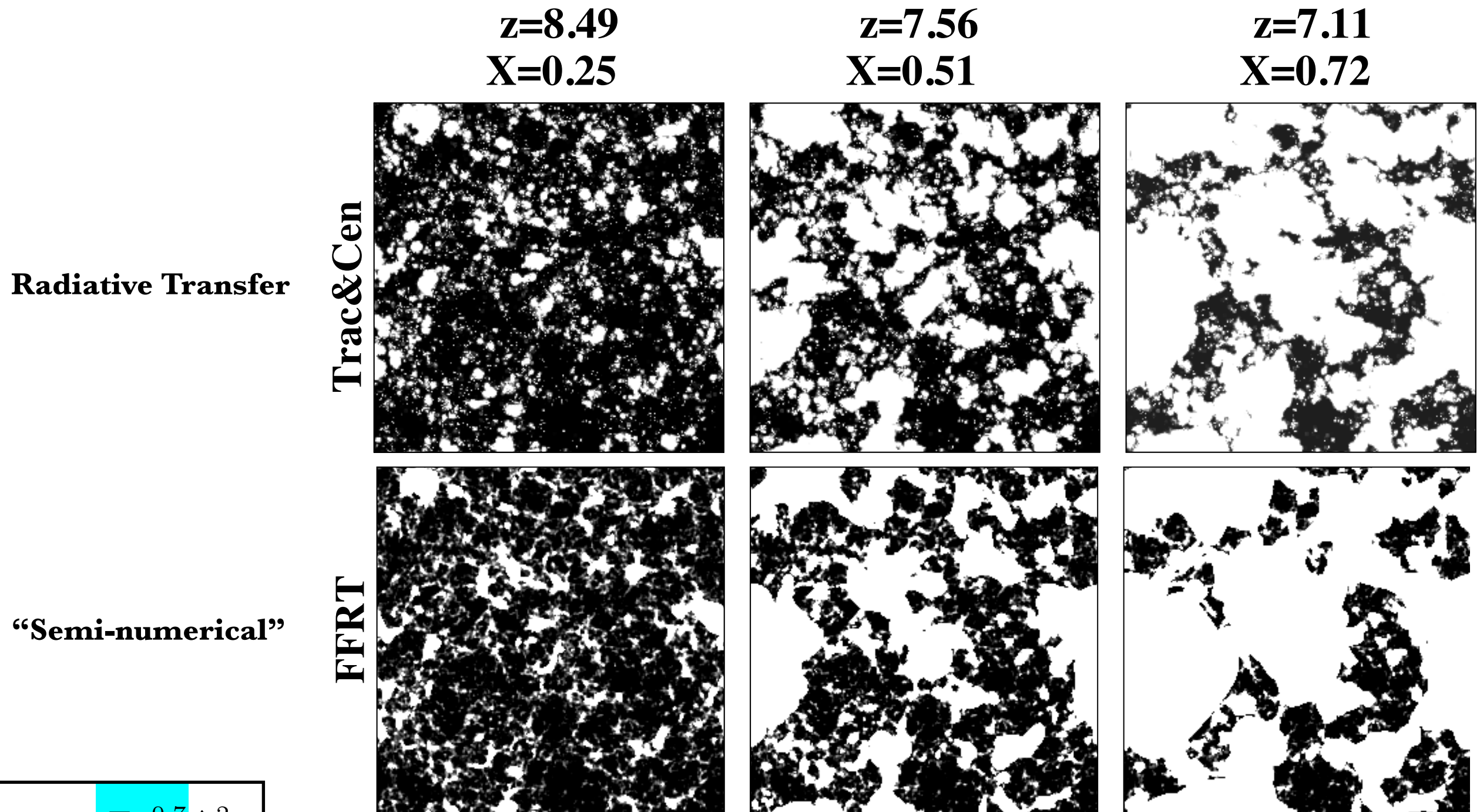
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$$\tau_{\text{Ly}\alpha} \propto \frac{T^{-0.7} \Delta_b^2}{\Gamma}$$

Modeling Patchy Reionization

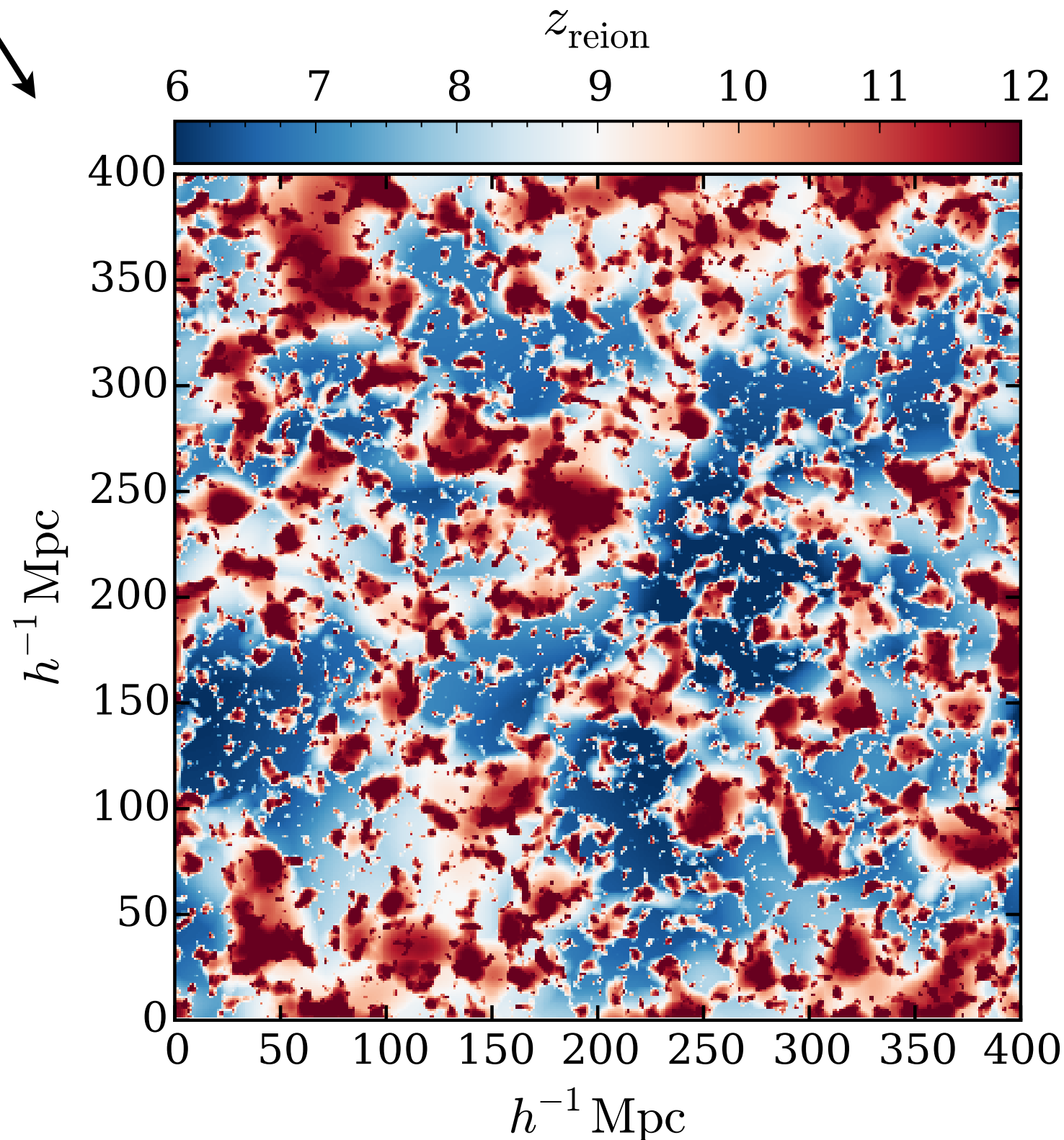
- Key feature of reionization: large-scale ionization structure traces source clustering
(Furlanetto, Zaldarriaga & Hernquist 2004)



$$\tau_{\text{Ly}\alpha} \propto \frac{T^{-0.7} \Delta_b^2}{\Gamma}$$

Modeling Patchy Reionization

Reionization redshift field traces large scale density fluctuations



Model parameters:

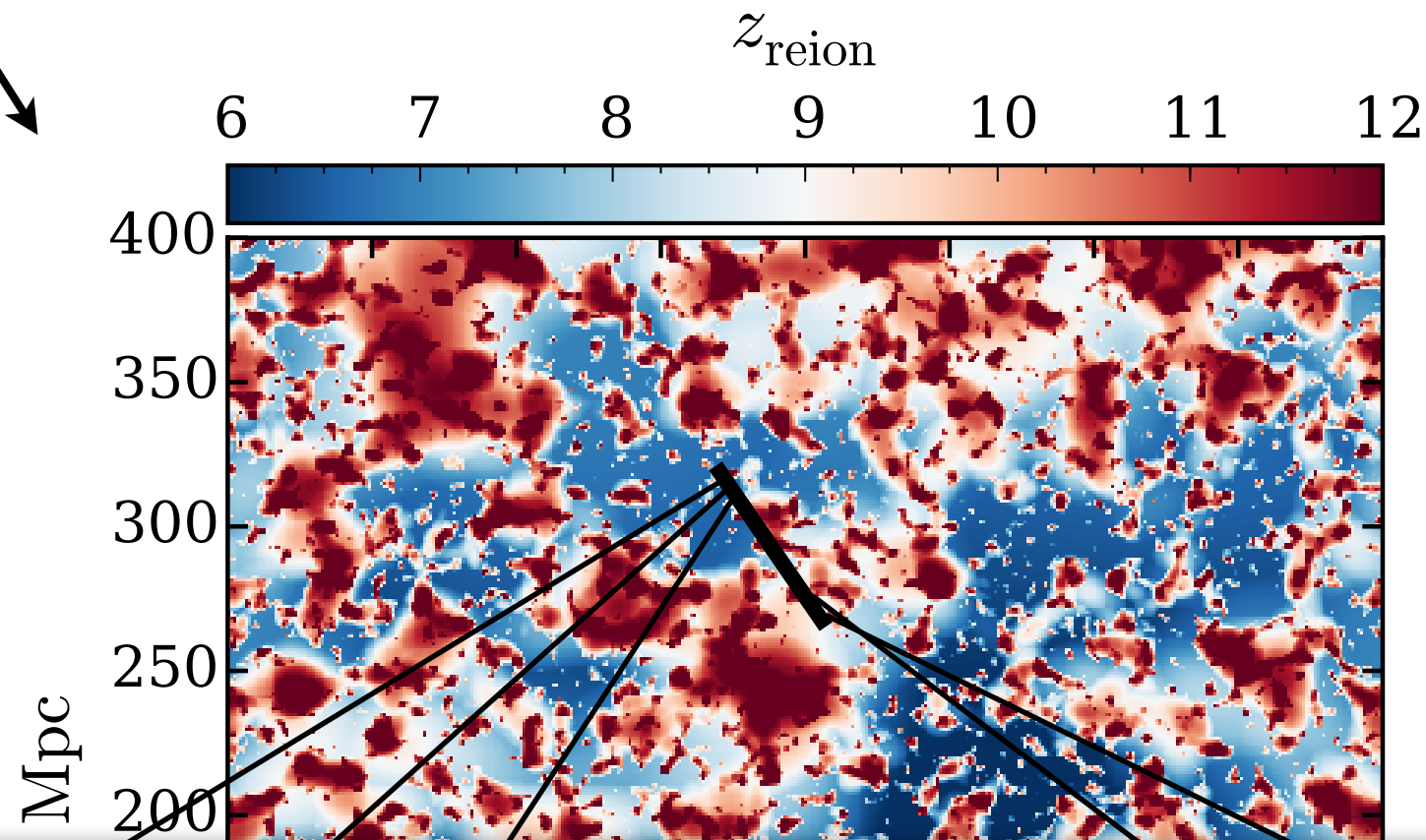
$$M_{\text{min}} = 2 \times 10^9 M_{\odot}$$

ζ (Ionizing Efficiency)

$$\tau_{\text{Ly}\alpha} \propto \frac{T^{-0.7} \Delta_b^2}{\Gamma}$$

Modeling Patchy Reionization

Reionization redshift field traces large scale density fluctuations



Model parameters:

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Mock Ly α forest spectrum

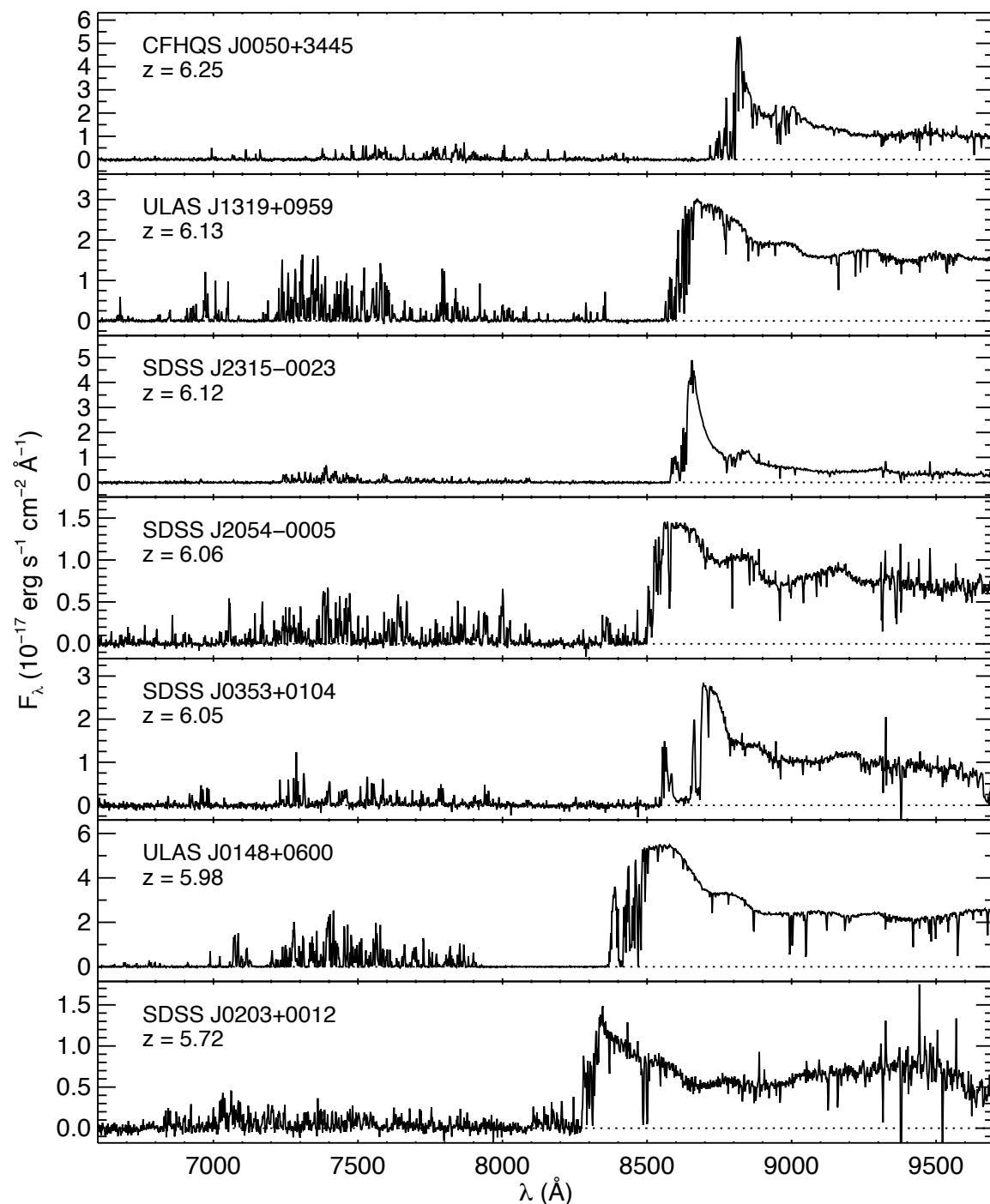
$z_{\text{reion}}^{(1)}$ $z_{\text{reion}}^{(2)}$ $z_{\text{reion}}^{(3)}$... $z_{\text{reion}}^{(N-1)}$ $z_{\text{reion}}^{(N)}$

0 50 100 150 200 250 300 350 400
 $h^{-1} \text{ Mpc}$

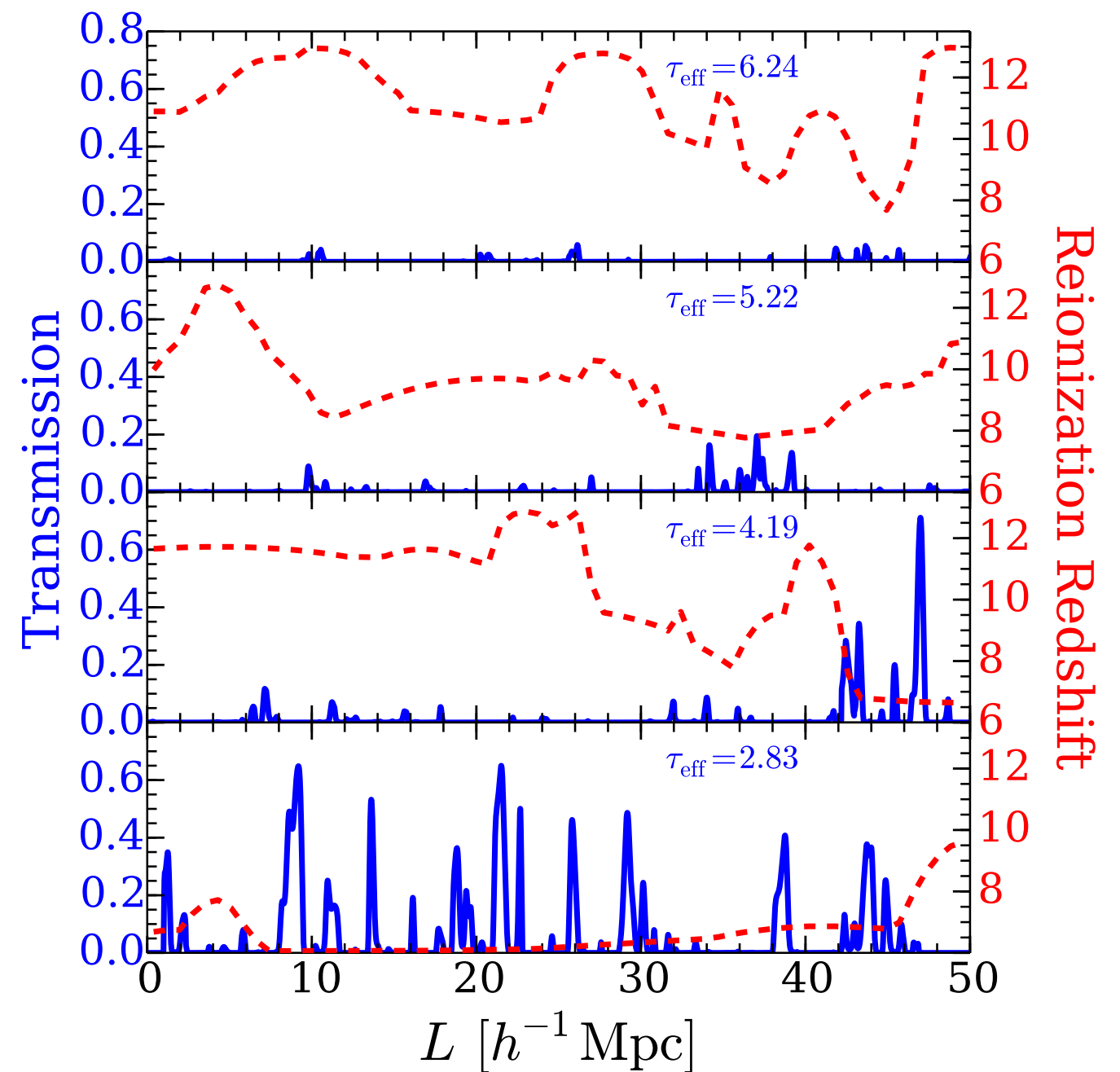
$$\tau_{\text{Ly}\alpha} \propto \frac{T^{-0.7} \Delta_b^2}{\Gamma}$$

Large Variations in the High- z Forest

(Observed, from [Becker et al. 2015](#))



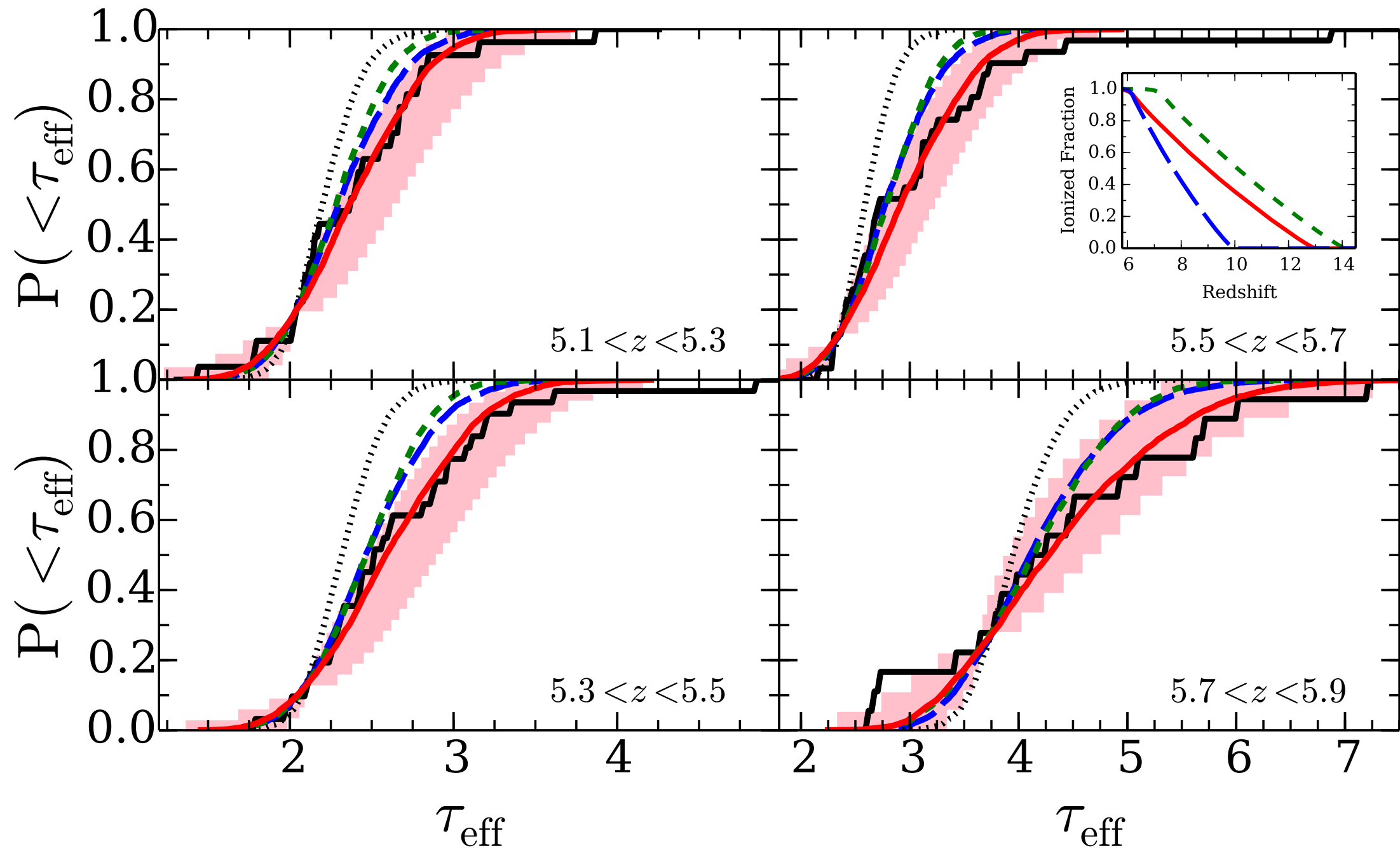
(Simulated, $z = 5.8$)



Darkest segments were reionized earliest!
New window into cosmic reionization?

$$\tau_{\text{Ly}\alpha} \propto \frac{T^{-0.7} \Delta_b^2}{\Gamma}$$

Relic Temperature Fluctuations from Reionization



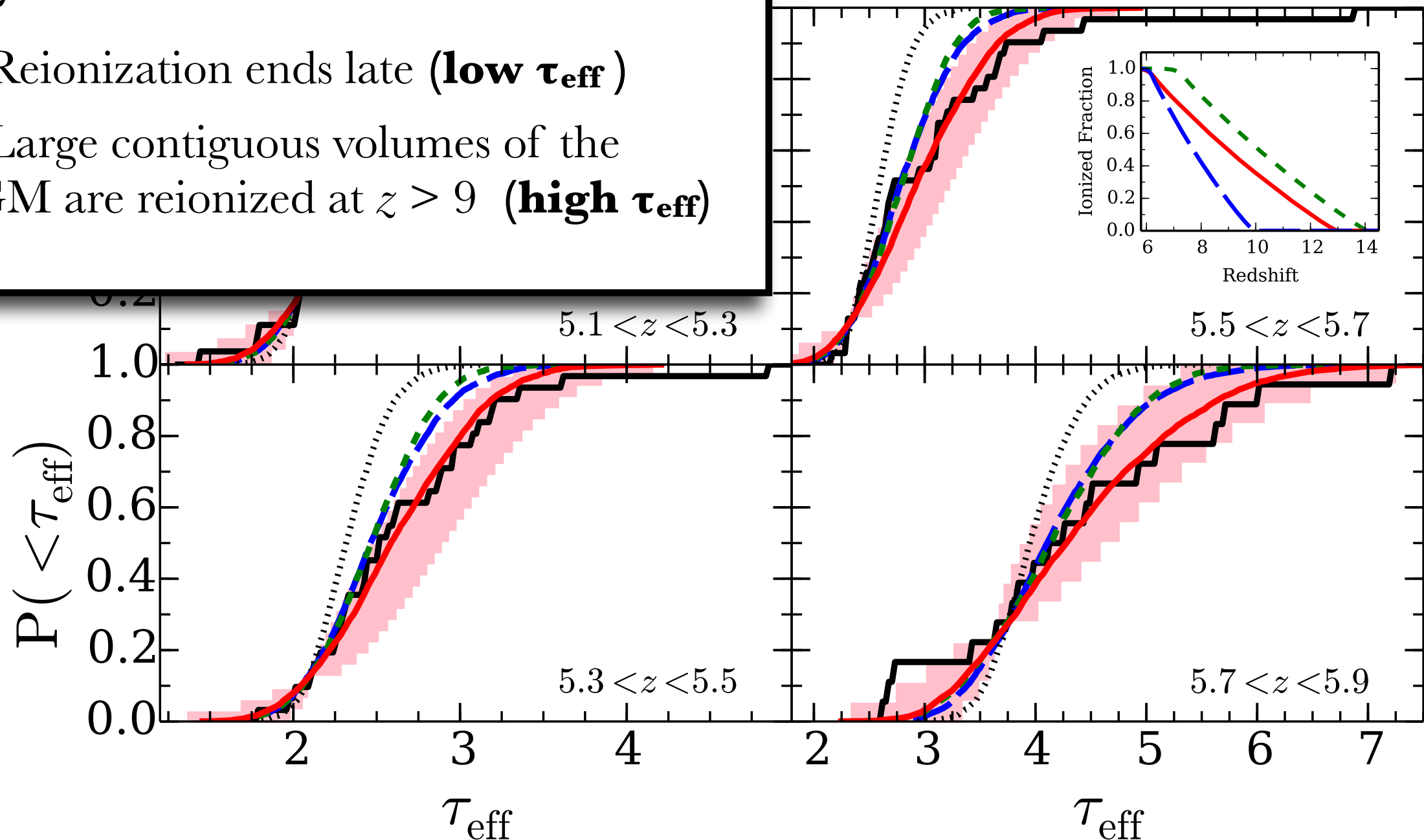
- Late but extended scenario ($z = 6 - 13$) works best.
- Matches observed evolution well; works at lower z too!

$$\tau_{\text{Ly}\alpha} \propto \frac{T^{-0.7} \Delta_b^2}{\Gamma}$$

Relic Temperature Fluctuations from Reionization

Key features of successful model:

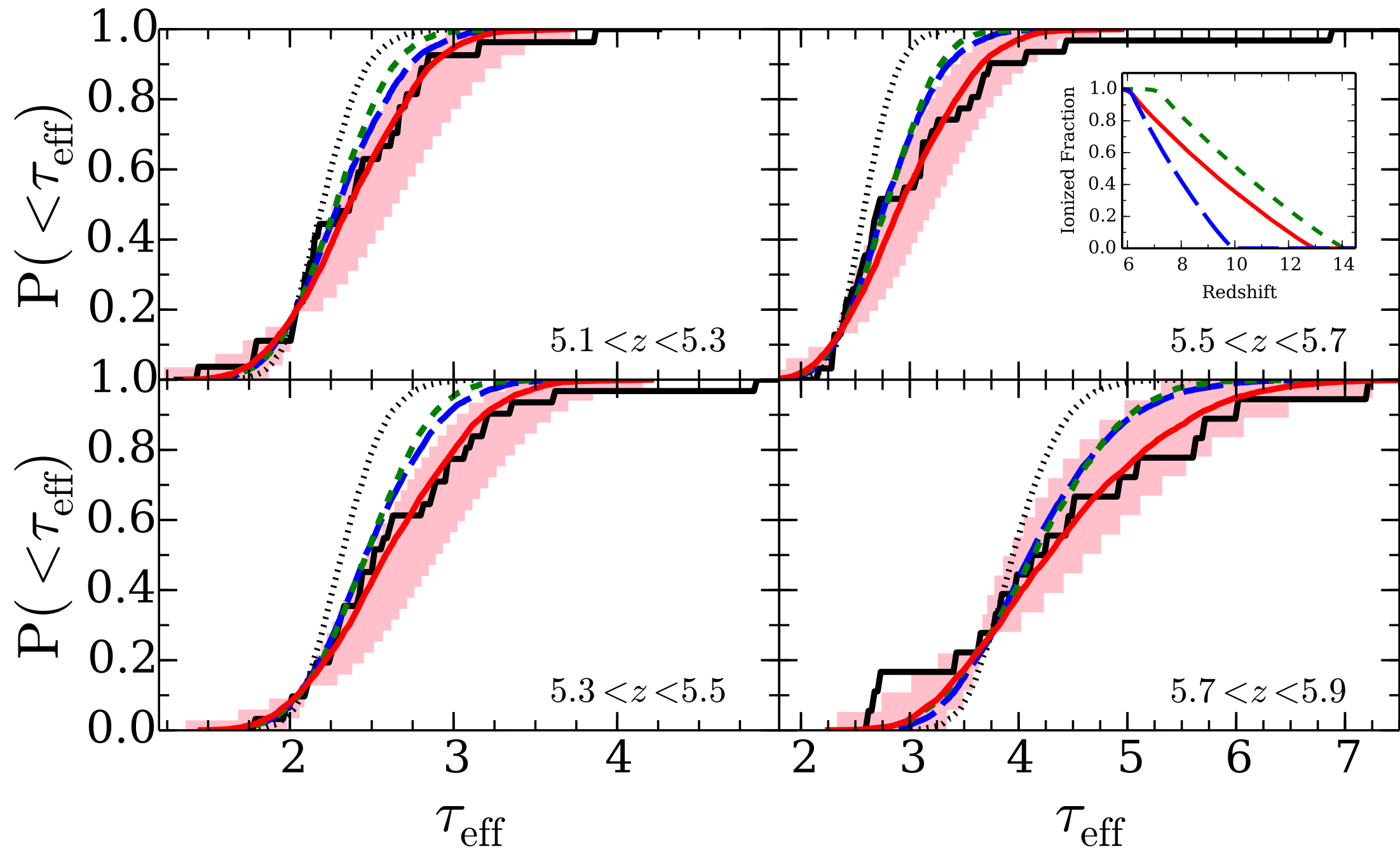
- Reionization ends late (**low** τ_{eff})
- Large contiguous volumes of the IGM are reionized at $z > 9$ (**high** τ_{eff})



- Late but extended scenario ($z = 6 - 13$) works best.
- Matches observed evolution well; works at lower z too!

$$\tau_{\text{Ly}\alpha} \propto \frac{T^{-0.7} \Delta_b^2}{\Gamma}$$

Relic Temperature Fluctuations from Reionization



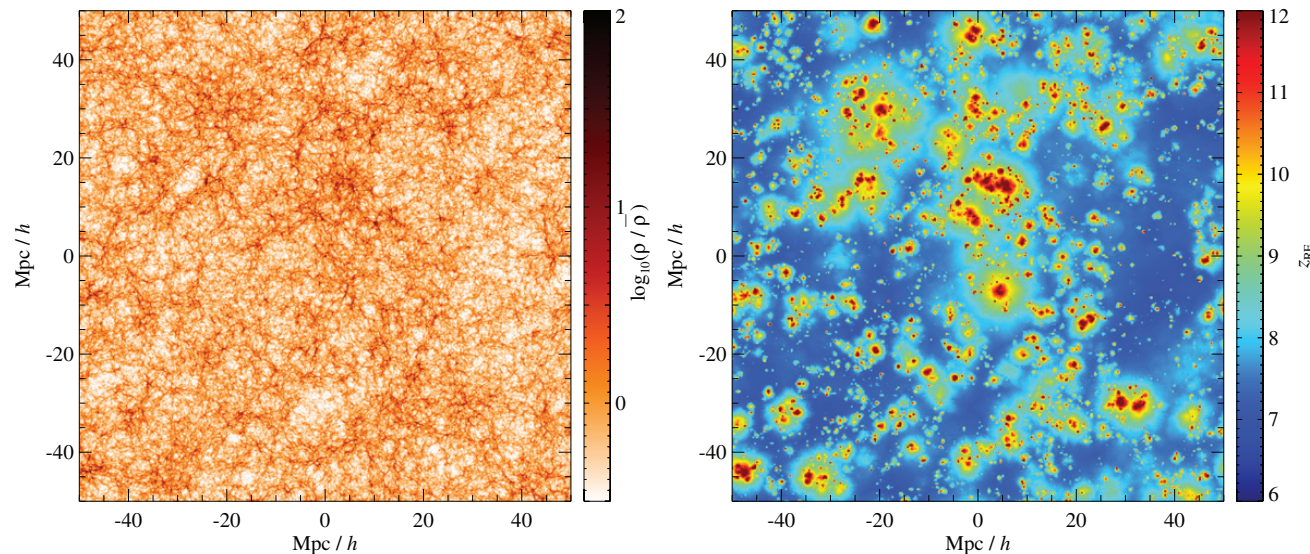
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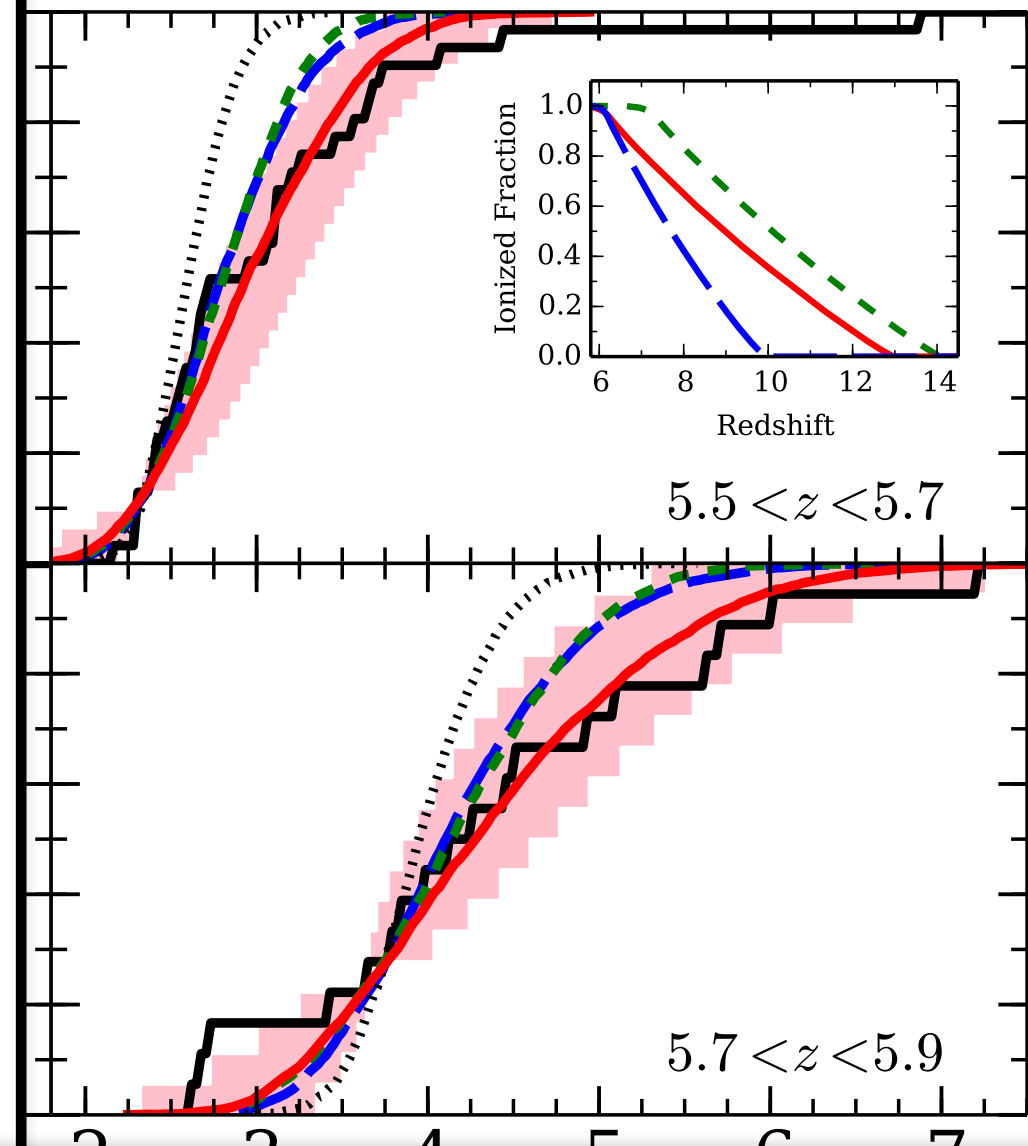
Relic Temperature Fluctuations from Reionization

Accounting for the highest opacities

- Model misses correlation between z_{reion} and local density
- Including this would only widen distribution



From Battaglia et al. (2013)



Mock Ly α forest spectrum



Conclusions

(3) Relic Temperature Fluctuations

Overdense regions are reionized first

At $z \sim 5.5$, they are colder

Higher equilibrium neutral H densities

Overdensities are the most opaque

(2) Spatially Varying Mean Free Path

Voids have lower ionizing background

Less sources

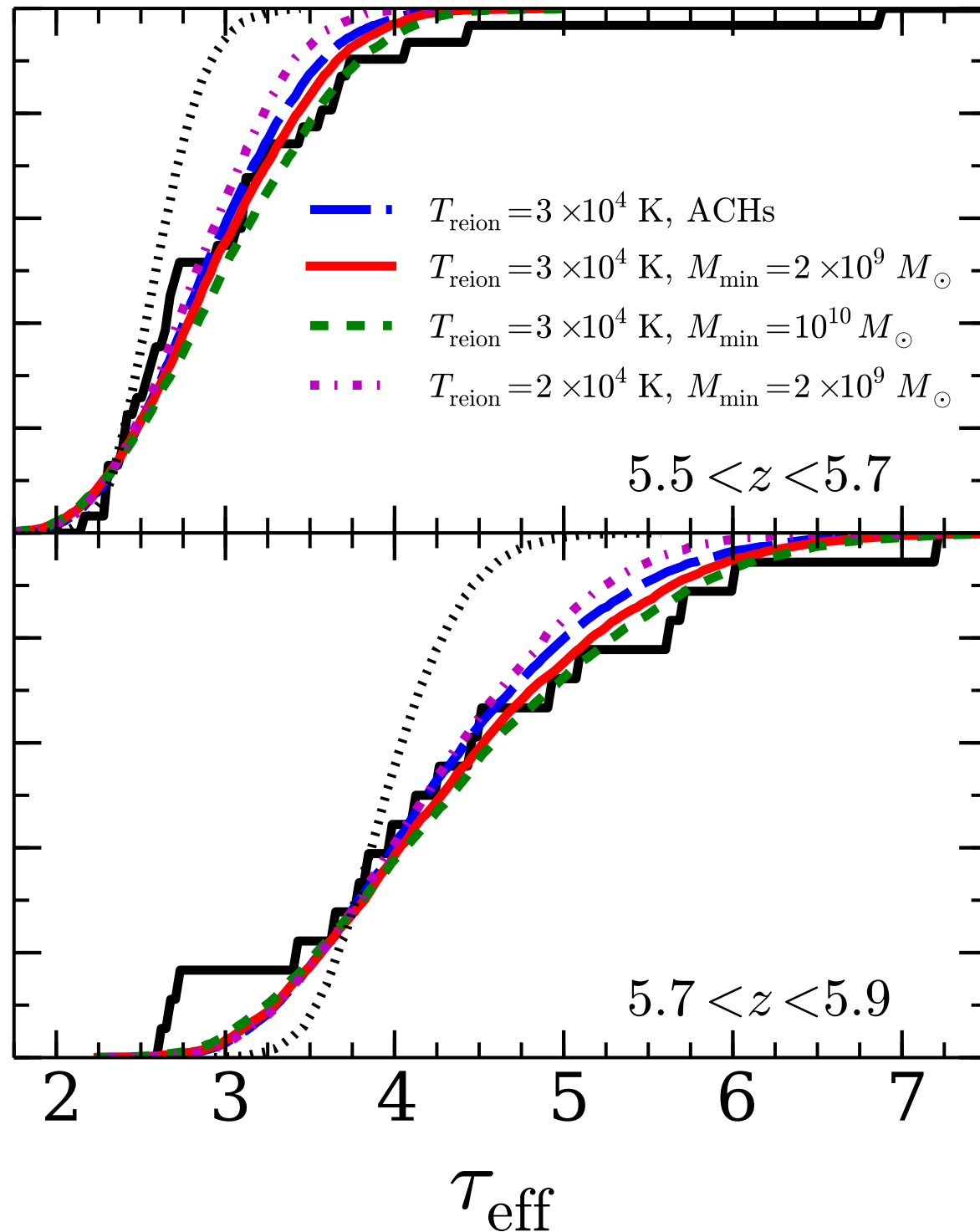
Absorbers are less ionized, smaller MFP

Voids are the most opaque

- If these two effects contribute significantly, they might cancel!
- They should be easy to distinguish observationally
 - Ly α forest/Galaxy cross-correlation
 - Higher-order Ly α forest statistics
 - For (3), shapes of transmission spikes in $z > 5$ forest
 - (3) \Rightarrow extended reionization: probe with kSZ

Backup Slides

Backup 1: Effect of Source Clustering and T_{reion}

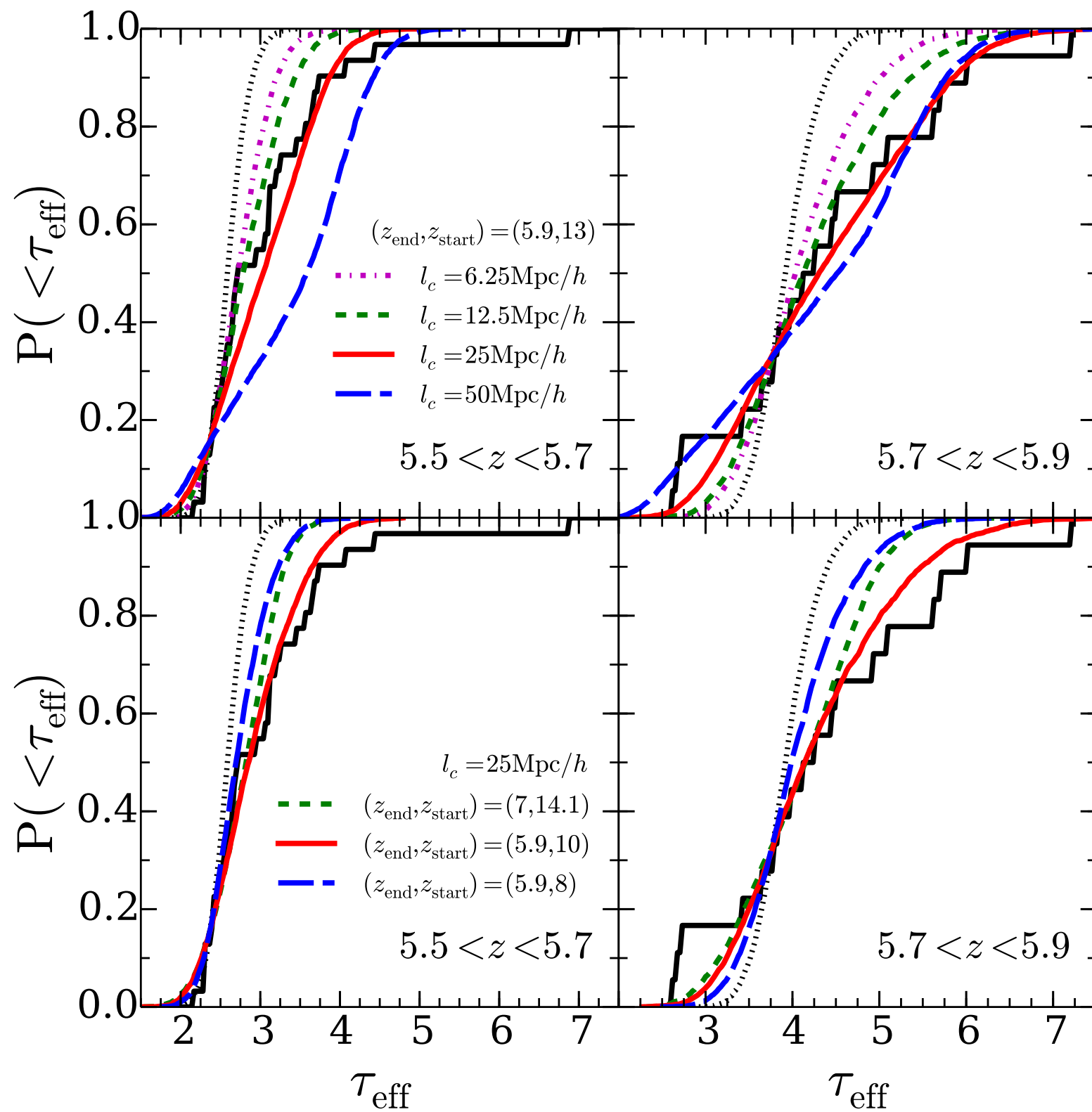


- Source minimum halo mass has only minor effect.

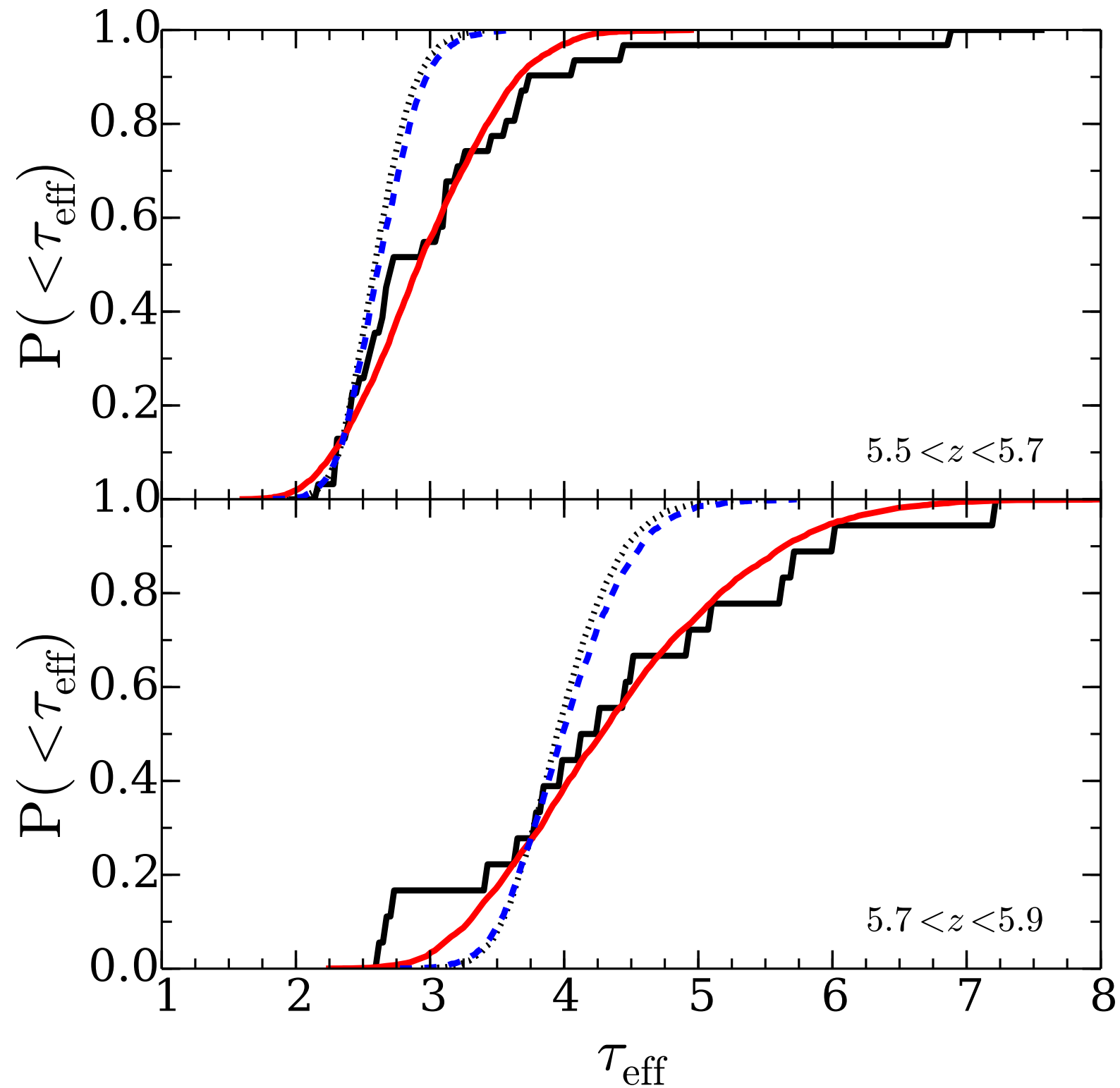
- Lower reionization temperature reduces width somewhat.

$$\tau_{\text{Ly}\alpha} \propto \frac{T^{-0.7} \Delta_b^2}{\Gamma}$$

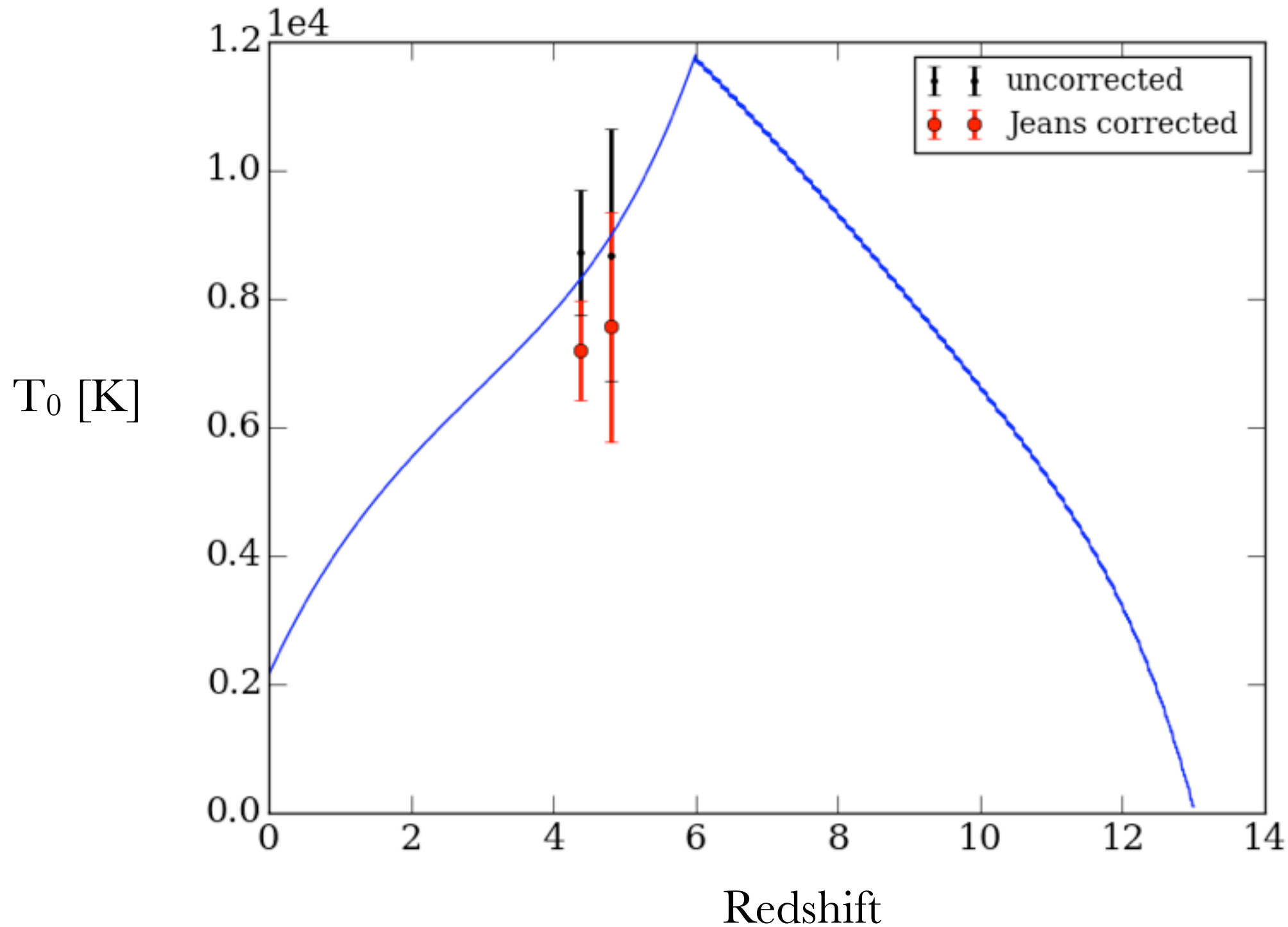
Backup 2: Toy Model



Backup 3: Effect of Jeans Smoothing

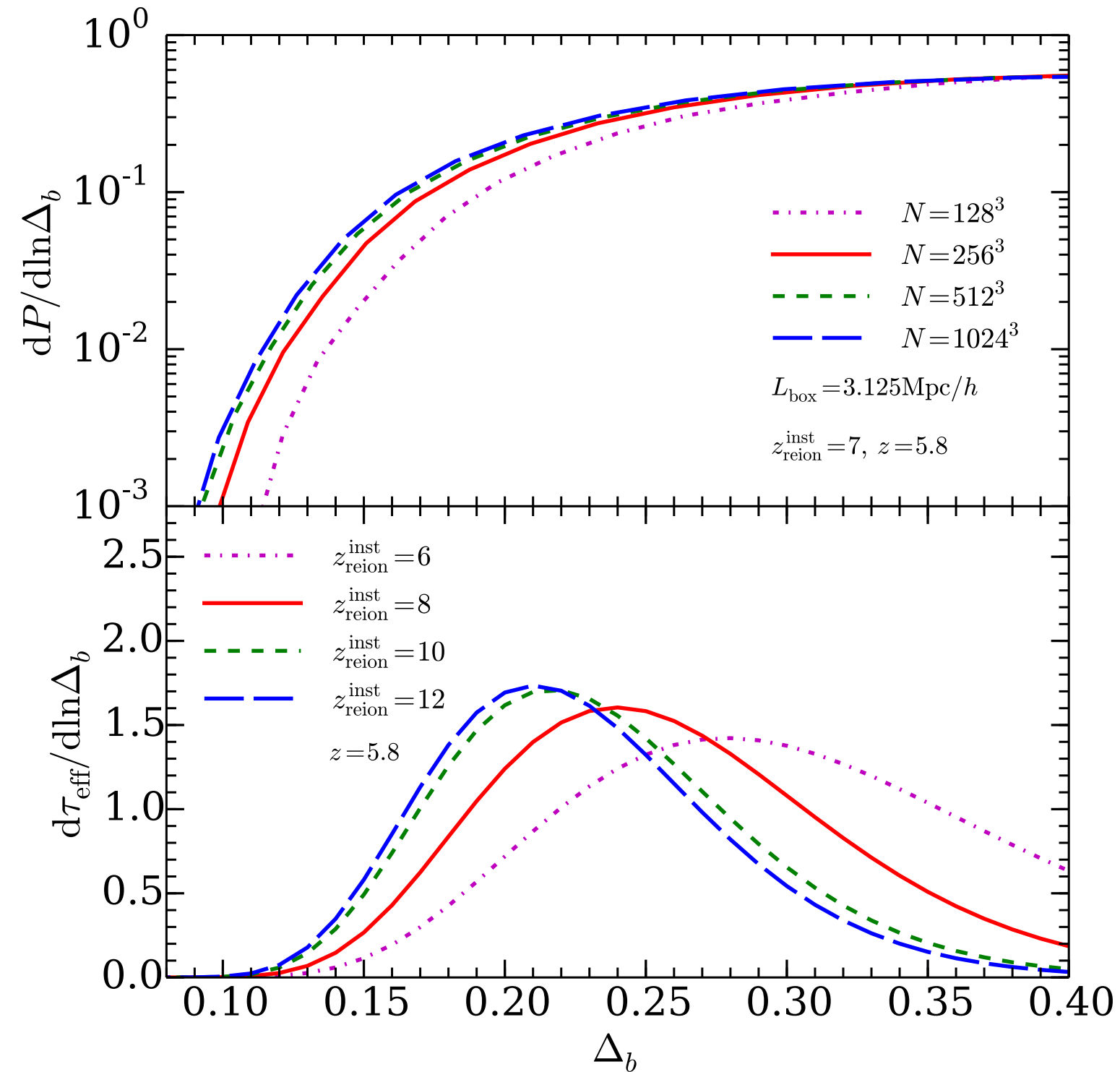


Backup 4: Consistent with Existing T Measurements

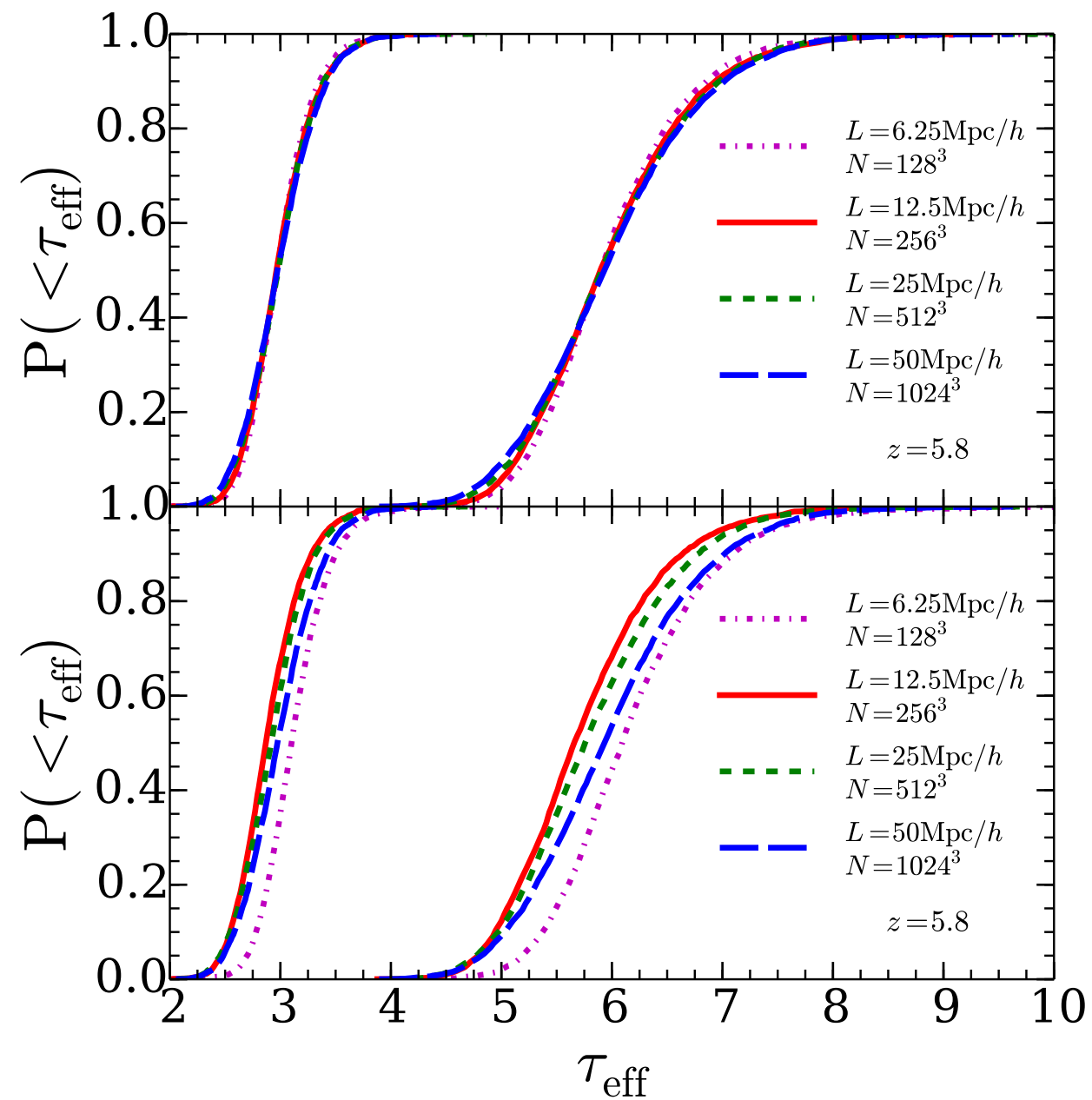
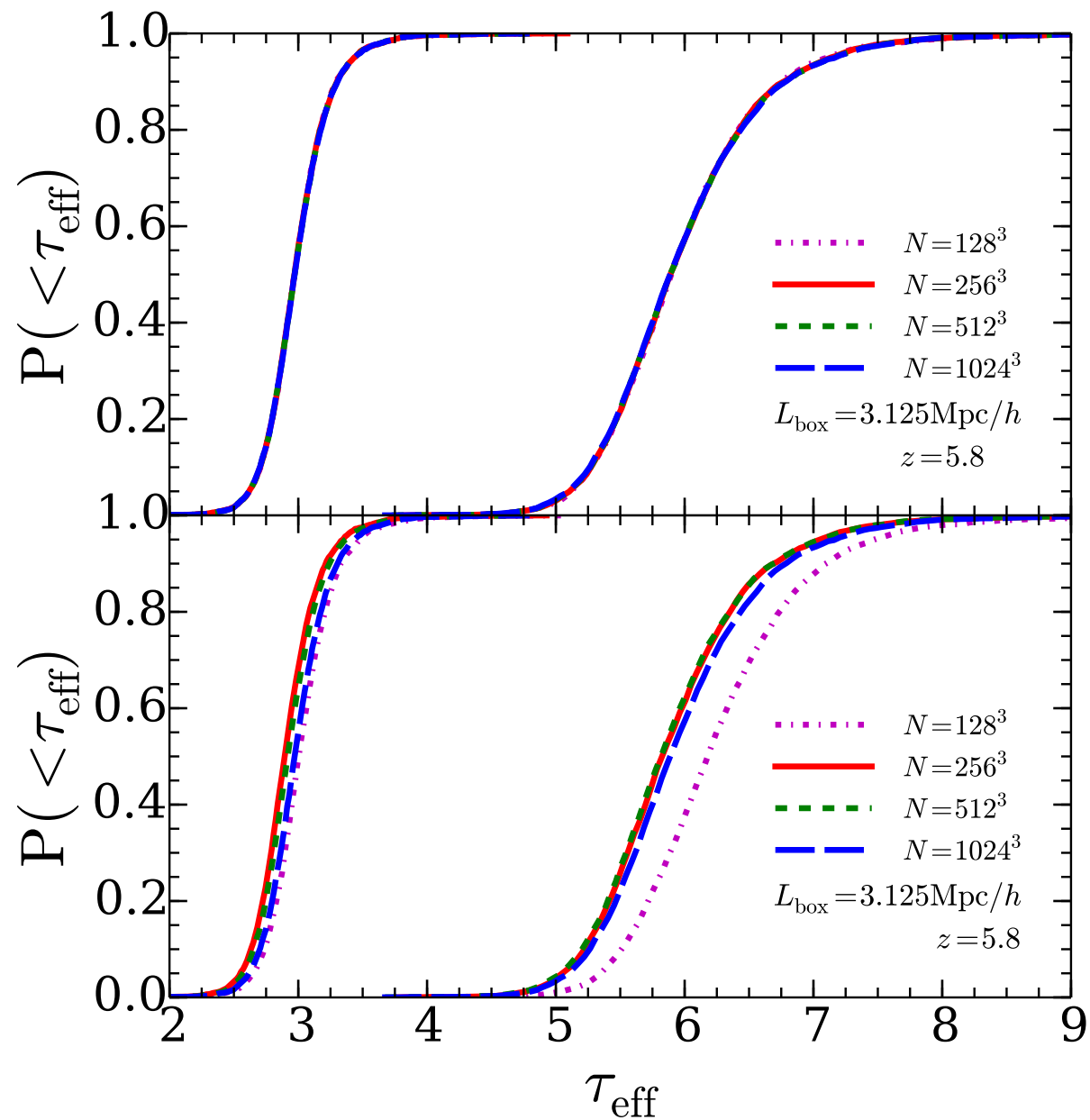


$$\tau_{\text{Ly}\alpha} \propto \frac{T^{-0.7} \Delta_b^2}{\Gamma}$$

Backup 5: Numerical Convergence



Backup 6: Numerical Convergence



Backup 7: Numerical Convergence

